Reservoir Trends and Exploration Potential of the El Vado Sandstone Member of the Mancos Shale, Northwestern New Mexico

by

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Dedication

To my family who have always supported me, to my sister Amber for encouraging me to pursue geology, and to Raul, my best friend, I could not have done this without you.

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Abstract

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The University of Texas at Austin, 2008

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The El Vado Sandstone Member (late Coniacian) of the Mancos Shale is considered by many to be an important unconventional hydrocarbon resource target (Ridgley, 2001) in the San Juan Basin located in northwestern New Mexico. The shelf sandstones of the El Vado were deposited along the western margin of the Western Interior Cretaceous Seaway. The El Vado is part of a transgressive-regressive wedge of rock that overlies a large, older transgressive wedge which contains the Tocito Sandstone (the largest oil producer in the basin). Despite its productivity in parts of the basin, the nature, origin, and distribution of the El Vado Sandstone is poorly understood.

Using well logs and core, the subsurface has been mapped to illustrate the distribution of the El Vado Sandstone across its extent in the San Juan Basin. The El Vado is reflected in logs as a thick (~ 120 foot) interval of low gamma ray and high

resistivity. The gamma ray log character reflects highly laminated sand-to-silts interbedded with shales. A total of 13 cross sections were constructed based on the high density of well log control. Isopach maps were then generated for the entire interval and individual cycles of the El Vado. Regional net sand and net-to-gross maps, determined from 104 digitized well logs, highlight the regional distribution of sand content.

Two regions in the basin were examined in outcrop, the northeast and the southeast. In the northern outcrops, the El Vado consists of five cycles of similar thickness (~ 4 m each) separated by marine shales with cycles becoming progressively sandier upward. To the south, the El Vado Sandstone appears to transition from a shelf deposited sandstone into a lower shoreface sandstone.

Examining the El Vado Sandstone in the subsurface and in outcrops helped the author to improve the understanding of the nature and distribution of the sands throughout the basin.

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Chapter 1: Introduction

Shallow marine sand bodies have been defined as accumulations of sand deposits between the shoreline and the shelf-edge (Johnson and Baldwin, 1986; Bergman and Snedden, 1999). Shallow marine sands, also know as shelf sands, have been a topic of debate amongst sedimentary geologists for years in numerous areas, yet the nature and origin of these sands remain poorly understood (Snedden and Bergman, 1999). Shelf deposited sand bodies (both isolated and sheets) have an importance among petroleum geologists because they form many major hydrocarbon reservoirs around the world and within the continental United States (once the Western Interior Seaway), as shown in Table 1.1. Several interpretations have been put forward to explain the origin of these sand bodies, and in most cases with little new data (Suter and Clifton, 1999). These interpretations include the following taken from Suter and Clifton (1999):

(1) Tidal sand ridges within a mixed wave and tidal regime open embayment (Tillman, 1999) and/or estuary-mouth shoals (Elliot, 1995).

(2) Tide-dominated delta within an incised valley (Sullivan, et al., 1995, 1997; the "Exxon model")

(3) Transgressed forced regressive and lowstand shorelines (Bergman, 1994; Bergman and Walker, 1995, 1999)

(4) Storm-dominated shelf sand bodies (Spearing, 1976; Tillman and Martinsen, 1984; Swift and Parson, 1999)

(5) Some combination of any or all of the above

Unit/Location	Age	Interpretation and Citation
Lower sandstone member of Thermopolis Shale, Montana	Cretaceous	Shelf sand ridges (Stine and Schmitt, 1987)
Mooreville Chalk, east-central Alabama	Cretaceous	Shelf sand bar (King, 1987)
Cardium Formation, Pembina Field, Alberta	Cretaceous	Lowstand shoreface (Plint, 1988); Shelf sand ridge (Krause and Nelson, 1991)
Olmos Formation, Webb County, Texas	Cretaceous	Shelf ridge and sheet sands (Snedden and Jumper, 1990)
Holder Formation, Sacramento Mountains, New Mexico	Pennsylvanian	Shelf sand ridges (Carr and Scott, 1990)
Tocito Sandstone, San Juan Basin, New Mexico	Cretaceous	Shelf sand ridge (Nummedal et al.,1993)
Shannon Member of Cody Shale, Hartzog Draw Field, Wyoming	Cretaceous	Lowstand shoreface (Walker and Bergman, 1993; Bergman, 1994); Tidal-estuarine valley fill (Sullivan et al., 1997)
Viking Formation, Alberta, Canada	Cretaceous	Lowstand shoreface (Walker and Wiseman, 1995)
Kenilworth Member, Book Cliffs, Utah	Cretaceous	Lowstand shoreface (Pattison, 1995)
Haystack Mountains Formation, southeast Wyoming	Cretaceous	Incised valleys and estuaries (Mellere and Steel, 1995)
Oseberg Sandstone, North Sea	Jurassic	Lowstand wedge prograding complexes (Muto and Steel, 1997)

Table 1.1: Ancient shallow marine sand bodies and their interpretation. Modified from Snedden and Bergman (1999).

Improving our knowledge of the origin and the nature of these offshore sands has several important implications. First, as stated in the previous paragraph, these sand types form major hydrocarbon reservoirs and growth in our understanding can have significant economic importance. Secondly, deciphering the true depositional nature of these sand bodies has the potential to impact paleoclimatic and paleooceanographic models of the Cretaceous (Slingerland and Keen, 1999). Thirdly, understanding the nature of these units has been claimed as the cause for a nearly 40 percent increase success of infill drilling in associated hydrocarbon fields (Sullivan, et al., 1997). The direct economic implications are obvious. Finally, these questions and answers can (based on previous statements) have an impact on models of exploration for these and similar deposits around the world. Determining the correct depositional model of shelf sands is critical, as the various interpretations imply significant differences in exploration approach and production characteristics (Bergman and Snedden, 1999).

THE EL VADO SANDSTONE MEMBER OF THE MANCOS SHALE

The El Vado Sandstone Member of the Mancos Shale (Landis and Dane, 1967) is part of a transgressive-regressive wedge of rock that overlies the Gallup unconformity in the San Juan Basin, located in northwestern New Mexico (Figure 1.1). The entire El Vado interval was deposited during a largely regressive time, with individual packages within the unit displaying deposition during smaller scale regressions. The shelf sands of the El Vado were deposited during the Coniacian, time equivalent to the Dalton Sandstone, along the western margin of Cretaceous Seaway (Figure 1.2). The El Vado Sandstone is often mistaken for the Tocito Sandstone, which is a similar aged sand unit often showing similar heterolithic character. However, as this study will show, there are many differences between these two units.

Like many shelf sand deposits, the El Vado Sandstone, which is considered an unconventional hydrocarbon resource target because of the low porosity and permeability, is a large oil and gas producer in the San Juan Basin; however, its nature and origin are poorly understood. It is the second largest oil producer (Tocito Sandstone is the largest) from the lower Mancos in the San Juan Basin (Ridgley, 2001) and has potential for more exploration in several fields. The El Vado has been underdeveloped in the basin because of lack of understanding of the sand and improper nomenclature on drilling reports, which have lead to a misrepresentation of productive formations in the basin.

Examining the El Vado Sandstone in the subsurface and in outcrops could help improve our understanding of the nature and distribution of the sands throughout the basin. This knowledge could lead to an increase in hydrocarbon production in certain regions and could help to exploit the shelf sands for their full potential. Lack of data and little exploration of the El Vado Sandstone make it an upside hydrocarbon target with huge potential in the San Juan Basin.

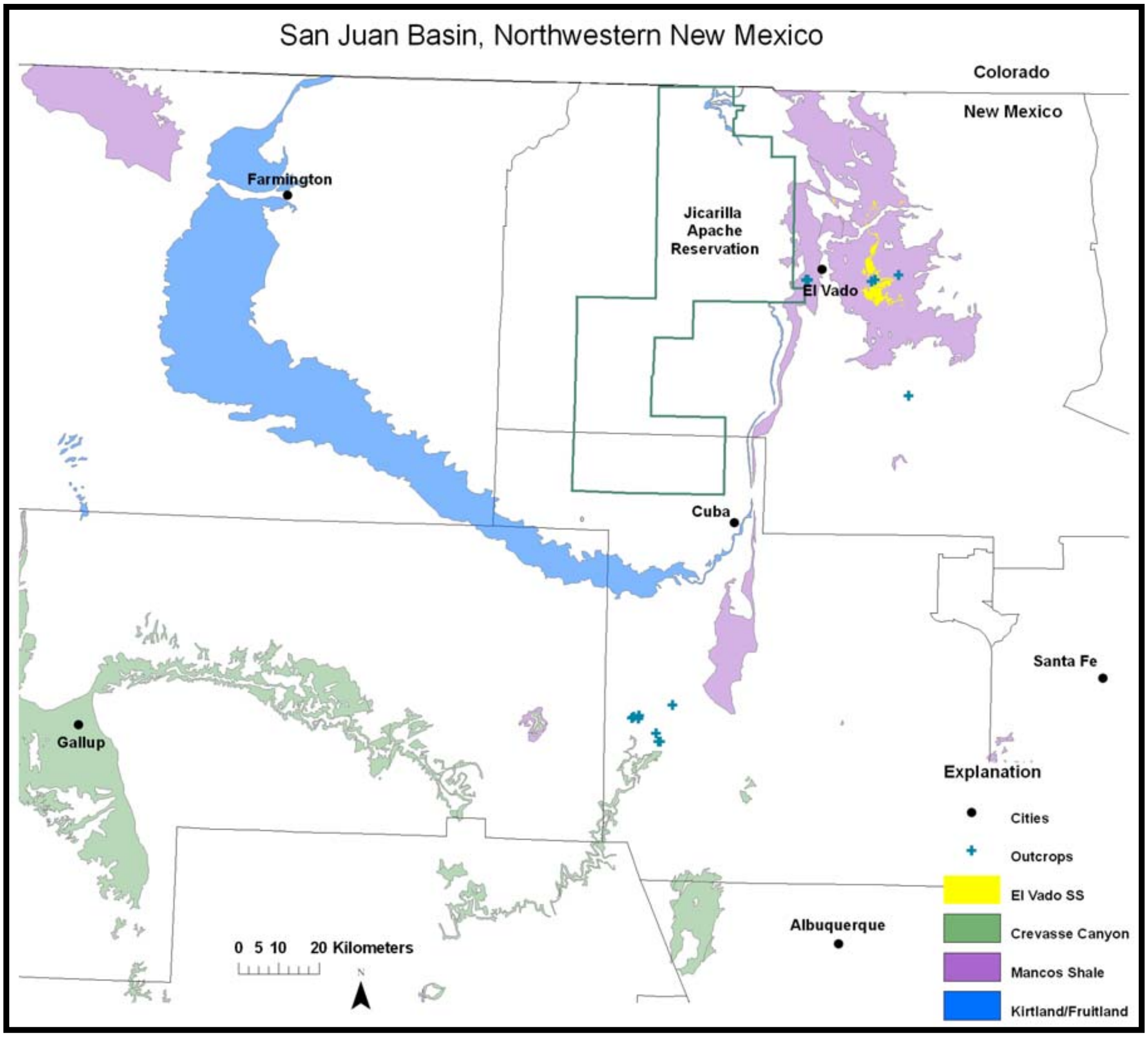


Figure 1.1: San Juan Basin is located in northwestern New Mexico and southwestern Colorado; Outcrops of the Fruitland Formation and Kirtland Shale are commonly used as the outline of the basin.

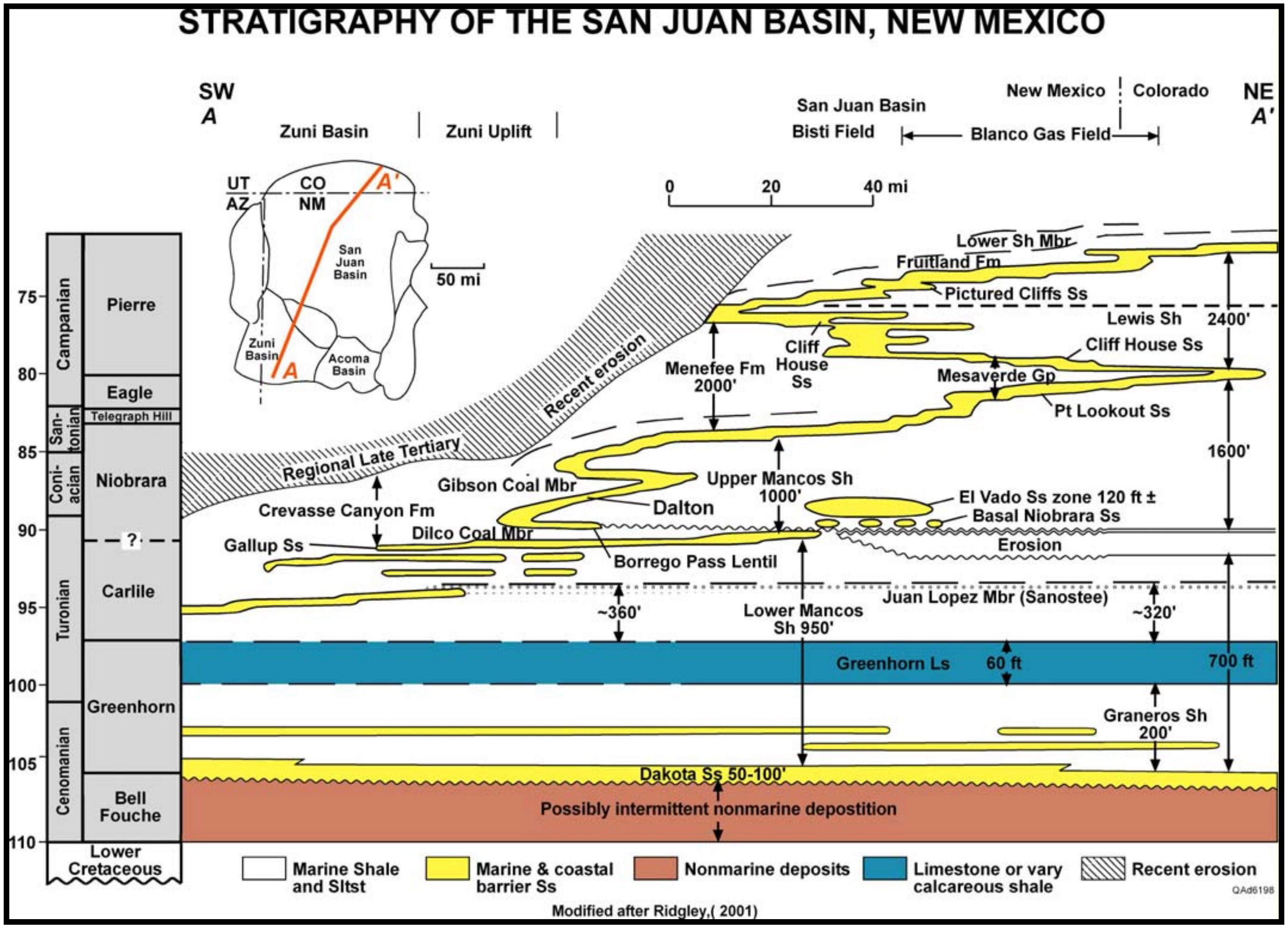


Figure 1.2: Stratigraphy of the San Juan Basin (modified after Ridgley, 2001).

OBJECTIVE

The focus of this study is to better understand the El Vado Sandstone and assess future potential of exploration within the unit in the San Juan Basin. At the onset of the study we immediately encountered several baffles to this process. Extremely limited biostratigraphic information within the unit, makes regional, basin-wide correlation of the El Vado and associated units very difficult. Also, as mentioned before, there has been an immense problem with drilling reports. In addition to the lack of chronostratigraphic marker fossils, the naming of the El Vado is inconsistent among industry workers in the basin. Driller reports and well top accounts refer to the El Vado by several names including, Tocito, Basal Niobrara, and Gallup Sands. This inconsistency in nomenclature makes it difficult, if not impossible, to track the production of the El Vado Sandstone.

REGIONAL STRUCTURAL SETTING

The San Juan Basin is located in northwestern New Mexico and part of southwestern Colorado (Figure 1.3). The outline of the basin is typically defined by the outcrop of the Fruitland Formation and the Kirtland Shale. It covers over 26,000 square miles and contains sedimentary rocks over two and half miles thick (up to 14,400 feet) ranging in age from about 570 to 2 million years in age, as seen in the simplified cross section of Figure 1.4 (Brister and Hoffman, 2002). The basin is a semi-circular asymmetrical bowl-shaped depression that is bounded mostly by monoclinal uplifts, as shown in Figure 1.3. The San Juan Basin has had a complex structural history; the final configuration was achieved during the Laramide orogeny in the Paleocene and Eocene (Woodward and Callender, 1977).

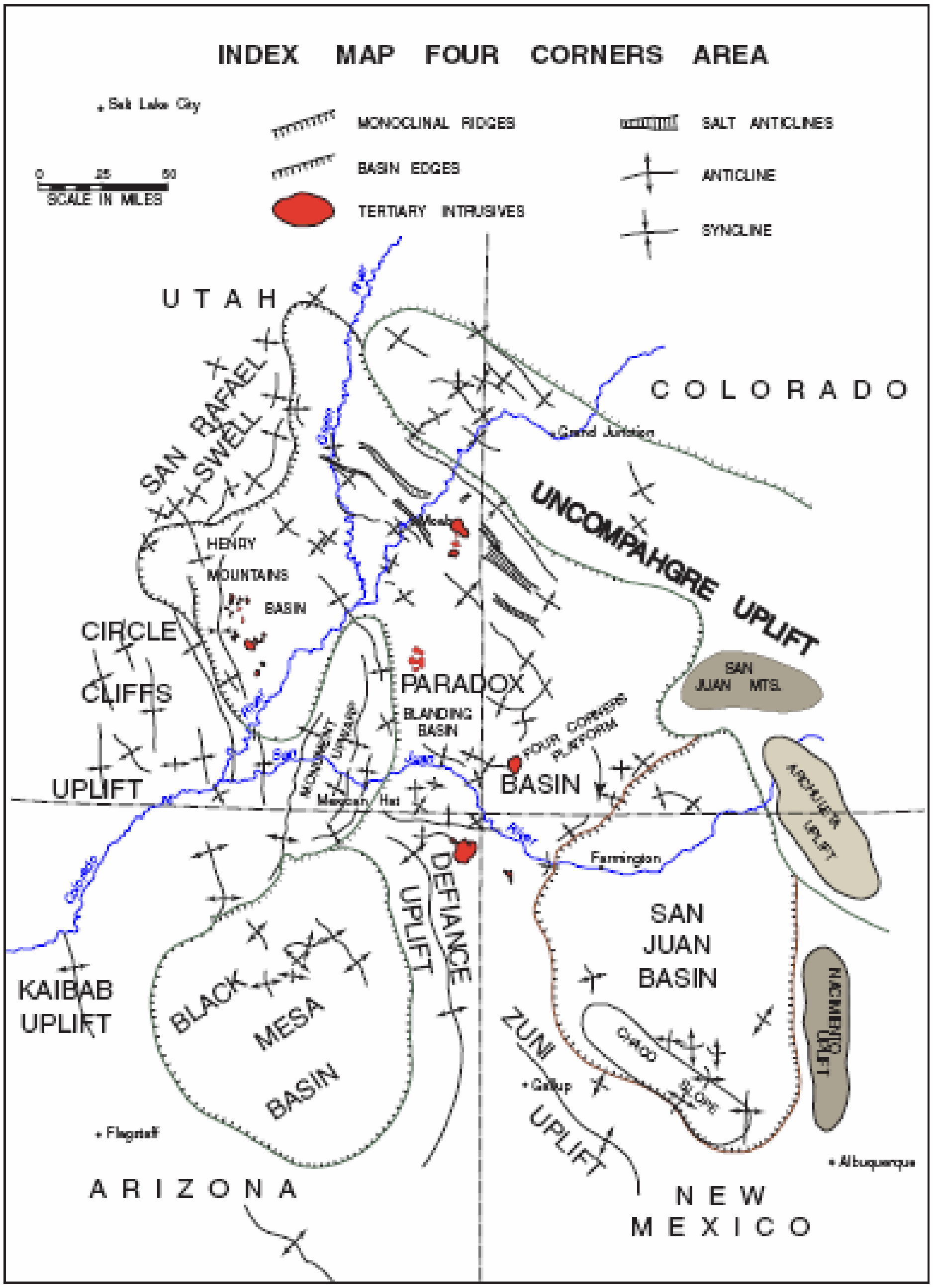


Figure 1.3: Regional map of the Four Corners area showing structural features (after Peterson, 1965; Devon internal document).

Until Pennsylvanian time, the basin depositional area was located on the northwest flank of the southwestward trending Trans Continental Arch. At that time, Late Mississippian, the entire area was emergent (Peterson, 1965). Between the end of the Mississippian and the beginning of the Tertiary, low areas were adjacent to a series of uplifts to the north, northwest, southwest and east. These low areas, oriented approximately north-south, allowed for the accumulation and preservation of most of the basin's fill (McGookey, 1972). The San Juan Basin, and many of the smaller structural details such as the mountains and hogbacks that define the basin boundary, began to form about 65 million years ago (Brister and Hoffman, 2002). The basin as we know it today is a Laramide-age feature that resulted as the North American plate drifted westward and impinged on the eastward dipping subduction zone. This continent-to-continent collision caused compression and created a predominant stress direction to the northeast resulting in northwest trending folds and northeast trending normal faults (Woodward and Callender, 1977).

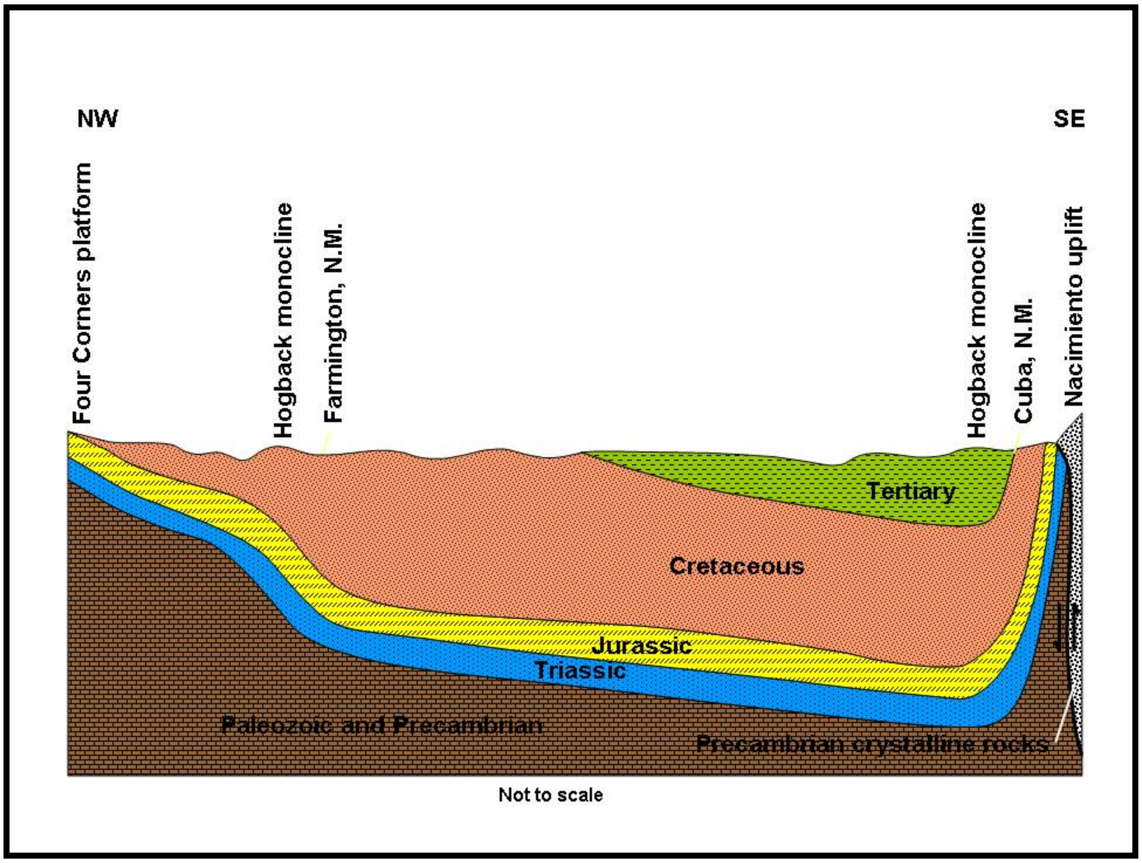


Figure 1.4: Simplified east-west cross section of the San Juan Basin (modified from Brister and Hoffman, 2002).

DISTRIBUTION OF HYDROCARBONS IN THE SAN JUAN BASIN

Load-induced subsidence and an abundant supply of sediment account for the thick accumulations of the clastics in the basin. The thickest sections of sedimentary rocks are found, present day, beneath the central part of the San Juan basin (Figure 1.4). The southwest part of the central basin is bordered by what is known as the Chaco slope, which dips gently to the northeast (Ridgley, 2001). The northeast side of the basin is defined by west-dipping monocline, which is comprised of a set of west-verging and east-verging thrust or reverse faults (Taylor and Huffman, 2000; Ridgley 2001). Several oil fields are found along the Chaco Slope and the type of hydrocarbon production is usually associated with the location of the field on the slope. Where the Chaco slope passes into the northeast and southwest parts of the central basin, hydrocarbon production is predominately gas, whereas oil production is dominant in the central part of the basin (Ridgley, 2001). Many oil fields have associated gas, which is generally found in the structurally highest part of the field (Ridgley, 2001).

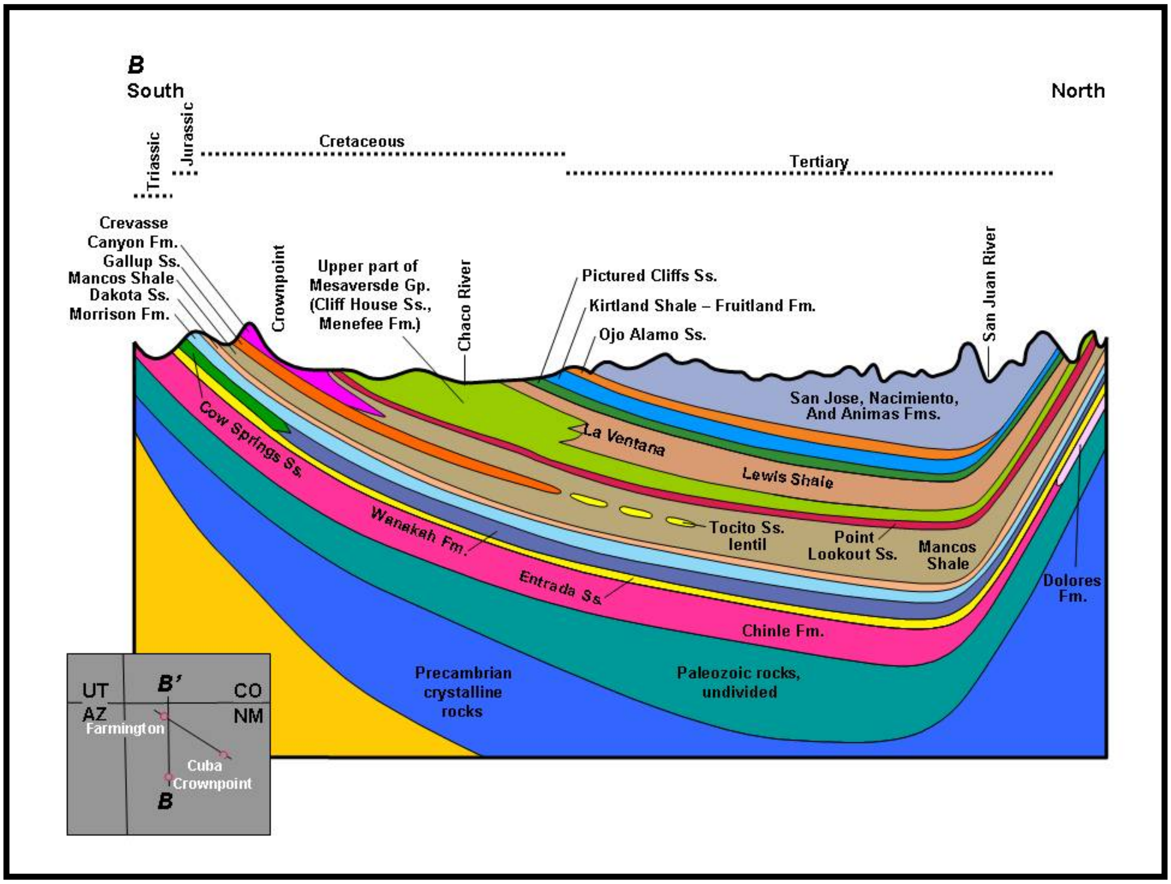


Figure 1.5: Southwest-northeast cross section of the San Juan Basin (modified from Brister and Hoffman, 2002).

STRATIGRAPHIC FRAMEWORK OF SAN JUAN BASIN

Exploration wells in the San Juan Basin show a sedimentary sequence of Precambrian basement overlain by Pennsylvanian, Permian, Triassic, Jurassic, Cretaceous, and finally Tertiary rocks, observed in Figure 1.4 (Beck and Hallett, 1997). Precambrian granite and metamorphosed supracrustal rocks (i.e. quartzites and schists) constitute basement lithologies throughout most of the basin (Woodward et al., 1977; Beck and Hallett, 1997). Above the basement rocks, the bulk of the basin is composed of sedimentary rocks from the Pennsylvanian through the Tertiary, during which time the basin went through many cycles of marine, coastal, and nonmarine types of deposition (Brister and Hoffman, 2002).

Pennsylvanian arkosic sandstone and arkosic limestones were deposited nonconformably on Precambrian rocks (Bingler, 1968; Beck and Hallett, 1997). Permian strata are composed entirely of reddish-brown arkosic clastics of the Culter Formation derived from the Uncompahgre uplift (Baars and Stevenson, 1977; Beck and Hallett, 1997). The Triassic was a time of nonmarine deposition, mainly consisting of various desert environments and by rivers and streams flowing into the region from the southeast (Brister and Hoffman, 2002). Triassic formations include the Chinle Group and the Rock Point Formation. Jurassic rocks are comprised of interbedded redbeds with cross-bedded sandstones (probably from windblown sand dunes), and lesser amounts of claystone, limestone, and gypsum, all of which make up the Entrada Sandstone, Todilto Formation, Summerville Formation, and the Morrison Formation (Beck and Hallett, 1997). The Entrada Sandstone is an oil reservoir in several fields that are along the Chaco slope and the Morrison Formation is a well known uranium-bearing unit in the southern part of the basin (Brister and Hoffman, 2002). A period of non-deposition and erosion followed the

Late Jurassic, and no sediments are preserved from the earliest Cretaceous in the San Juan Basin (Brister and Hoffman, 2002). Also, the upper contact of the Morrison Formation with the overlying Cretaceous strata is generally an unconformable scour surface (Stokes, 1952; Beck and Hallett, 1997). The majority of the sediments in the San Juan Basin were deposited during the Late Cretaceous. During this time the Western Interior Cretaceous Seaway (Figure 1.6) spilt the North American continent into two halves and the transgression and regression of the shorelines resulted in the deposition of thick packages of sediment.

Most of this section is Late Cretaceous but up to 200 feet of the Lower Cretaceous Burro Canyon Formation was deposited as well (McGookey, 1972). The Upper Cretaceous strata are composed of alternating marine and nonmarine coastal deposits of the Mancos and Mesaverde Groups resulting in close to 6,000 feet of sediment, which is shown partly in Figure 1.2 (Beck and Hallett, 1997). The vast majority of the hydrocarbons produced in the San Juan Basin come from the Upper Cretaceous strata and will therefore be discuss in more detail in the next section. From the end of the Cretaceous through the Tertiary the basin was dominated by nonmarine deposition from the continental San Jose and Nacimiento Formations (Brister and Hoffman, 2002). There is as much as 2,300 feet of the San Jose Formation present in the northern part of the basin. There was abundant volcanic activity in the north and southwest parts of the San Juan Basin starting in the Eocene time, peaking during the Oligocene and tapering off in the Miocene (Devon Energy, written internal document).

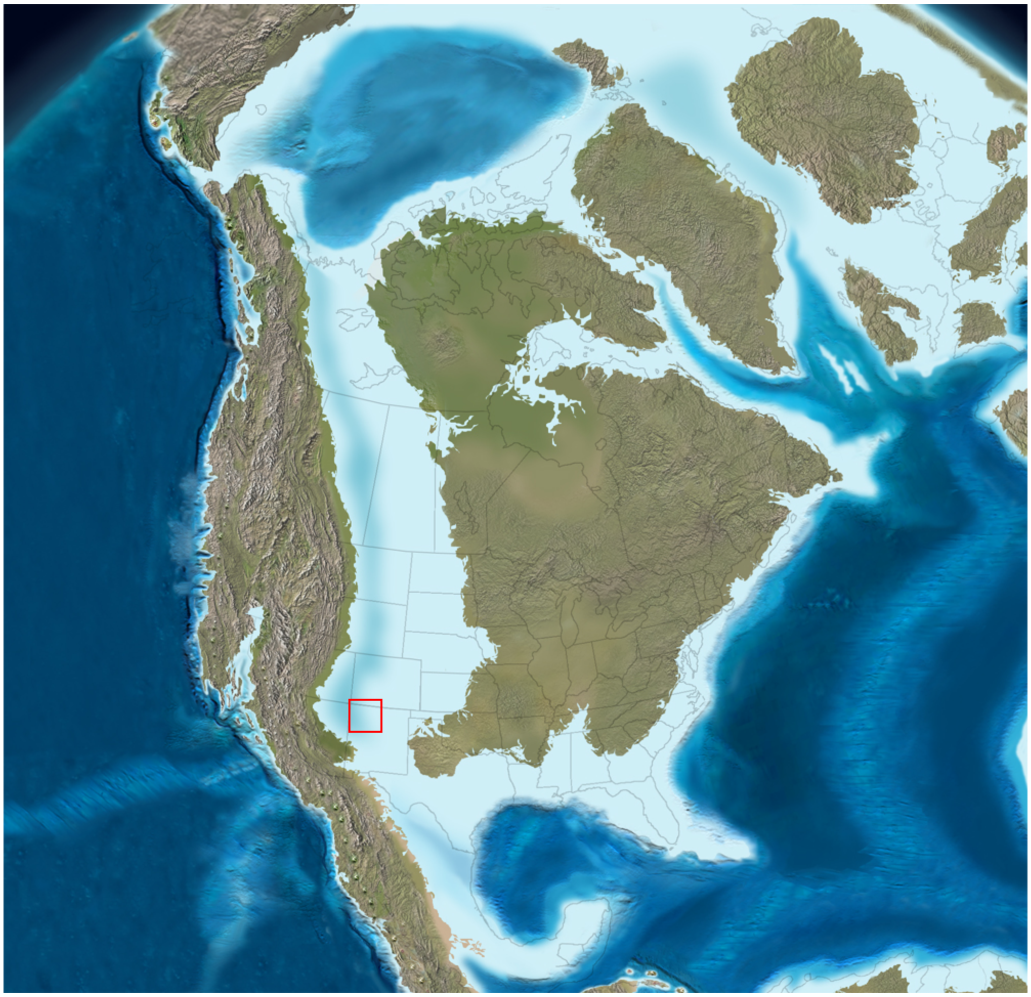


Figure 1.6: Western Interior Cretaceous Seaway, paleogeography from 85,000 years ago (Blakey, 2006). Red box indicates the San Juan Basin.

Cretaceous Stratigraphy

This study is focused primarily on the Upper Cretaceous sediments. In this section, the stratigraphy of those specific units will be described in more detail. Summaries of Cretaceous formations can be found in even more detail in the following papers (Ridgley, 2001; Fassett, 1974; Landis and Dane, 1967; Landis and other, 1974; Molenaar, 1974; 1977). The following descriptions are in chronostratigraphic order, beginning with the oldest unit.

Gallup Sandstone

The Gallup Sandstone in northwestern New Mexico is a northeastward prograding clastic wedge of the late Turonian to earliest Coniacian age that pinches out in the middle of the San Juan basin (Nummedal and Molenaar, 1995). Paleoenvironmental and sequence stratigraphic studies indicate that the Gallup is dominated by strand plain successions that prograded across a gently dipping ramp during repeated episodes of relative sea level fall (Nummedal and Molenaar, 1995). An almost continuous belt of Gallup Sandstone outcrops rim the southern, western, and southeastern parts of the San Juan basin allowing for extensive field studies (Nummedal and Molenaar, 1995). Figure 1.7 shows the different shorelines of the Gallup and the most seaward extend. Above the Gallup lies the basin wide unconformity that is often referred to the Gallup Unconformity.

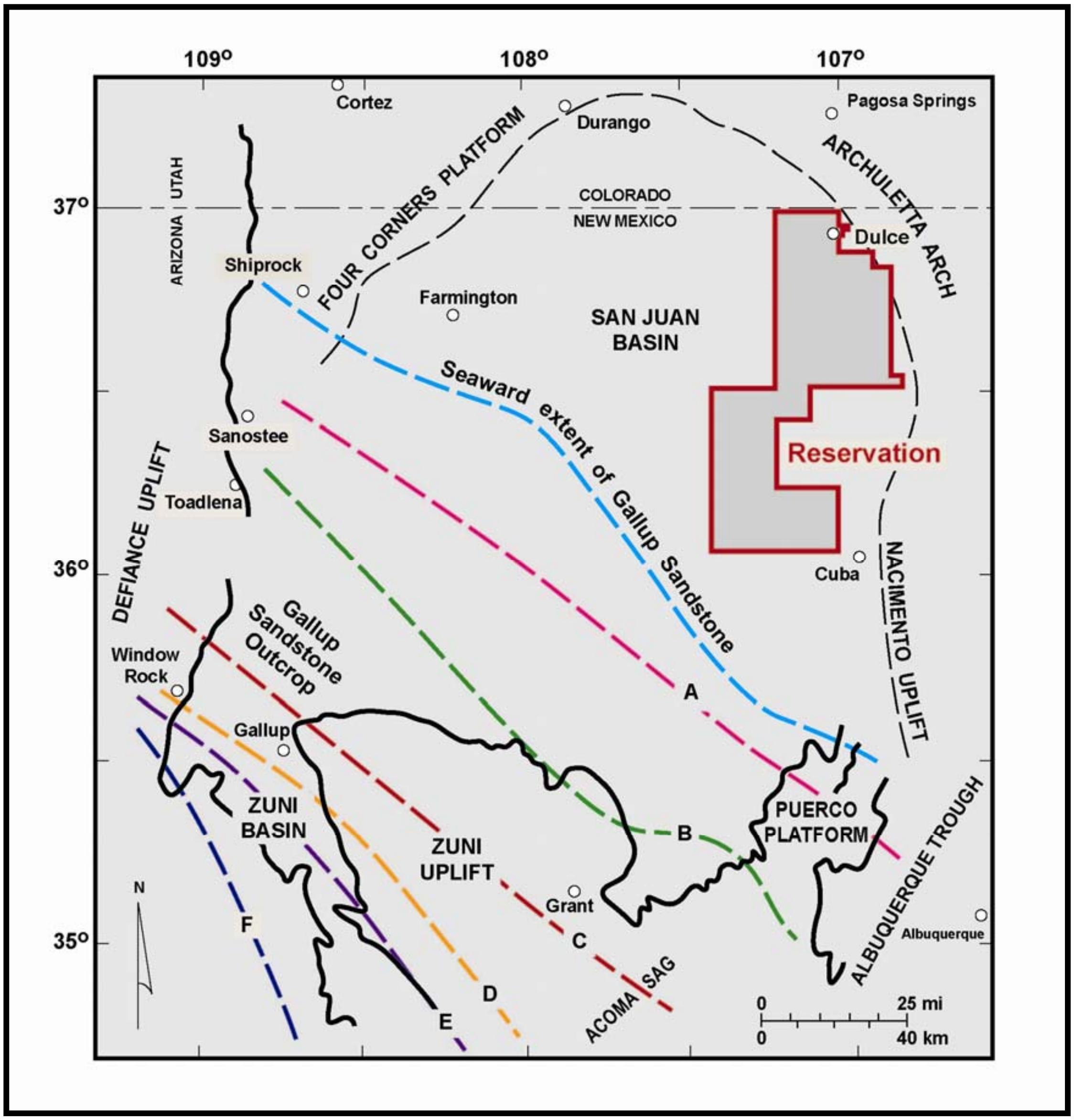


Figure 1.7: Map displaying the shorelines of the Gallup (dashed colored lines notated A, B, C, D, E, and F) across the San Juan Basin. Black solid lines reflect the present day outcrop extent. Dashed black lines mark the major structural uplifts bounding the basin (modified from Ridgley, 2001).

Crevasse Canyon Formation

The Crevasse Canyon Formation includes the rock interval between the top of the Gallup Sandstone and the base of the Mesaverde Group (Ridgley, 2001). The member of the Crevasse Canyon that is of interest to this study is the Dalton Sandstone. The Dalton Sandstone consists of a series of northward stepping regressive coastal barrier and shoreface sandstones; the lateral distal equivalents of the Dalton within the Mancos Shale are assigned to the El Vado Sandstone Member of the Mancos Shale (Ridgley, 2001). Figure 1.8 shows the current outcrops of the Crevasse Canyon and their relationship to the Mancos Shale outcrops.

Mancos Shale

The Mancos Shale covers an extensive portion of the San Juan Basin and consists in some areas of up to 1600 feet of dark gray to black calcareous and noncalcareous shale and sandstone of marine origin (Ridgley, 2001). The Mancos Shale is typically divided into two units, the Lower and Upper Mancos, as shown in the stratigraphic cross section (Figure 1.2). This division occurs at an extensive unconformity termed “the regionally unconformity”, sometimes called the Gallup unconformity. The units above the unconformity within the Upper Mancos Shale are the focus of this study. To the south, southwest, and northwest, the Mancos Shale intertongues with various clastic formations which represent the continental and shoreward facies that are laterally time-equivalent to the marine shale facies that define the Mancos Shale (Ridgley, 2001). The Mancos is also thought to be both the source and the seal of the oil and gas in the Cretaceous-aged Mancos reservoirs.

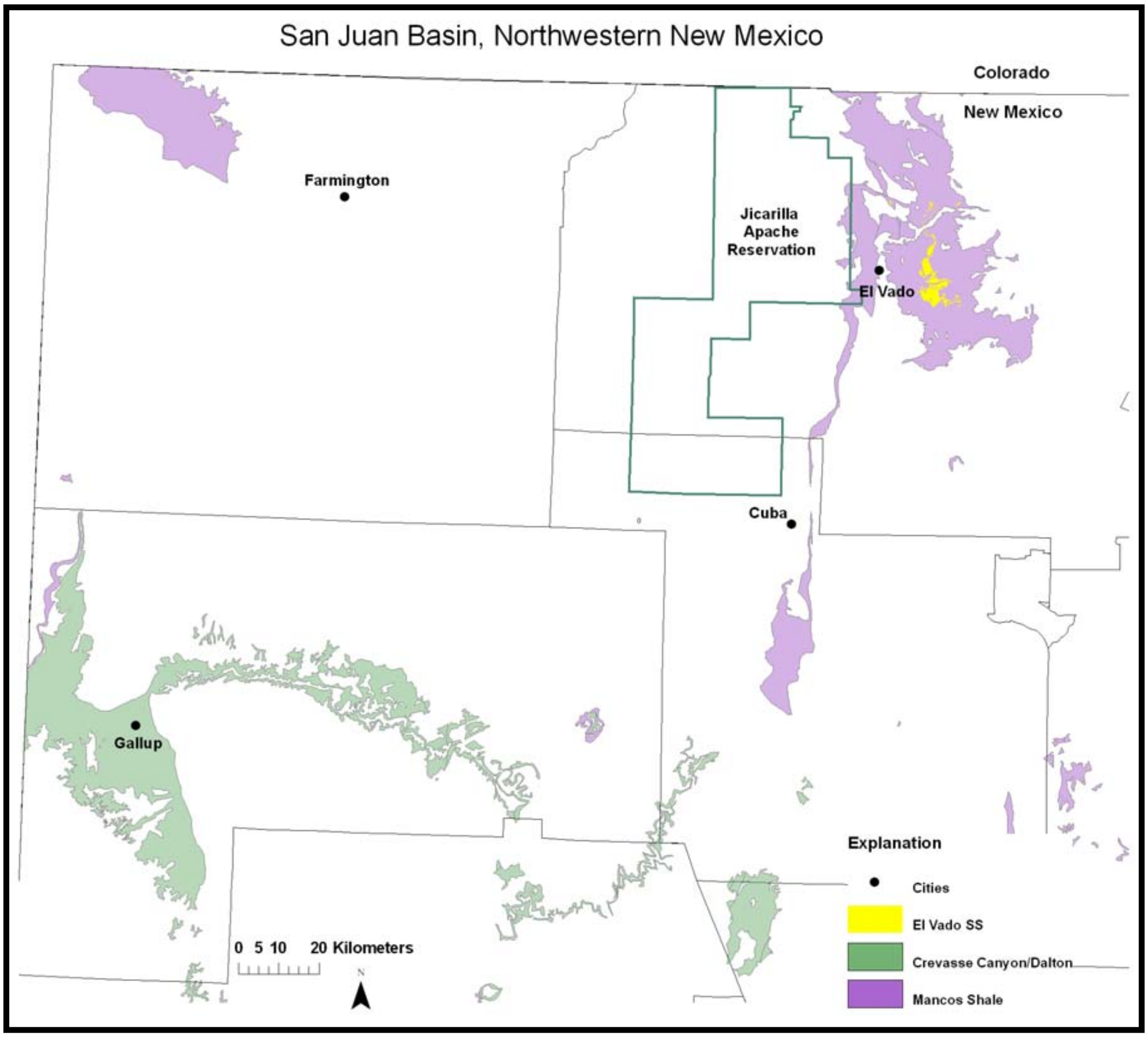


Figure 1.8: Outcrops of the Crevasses Canyon and the Mancos Shale in the San Juan Basin. Gray lines reflect county boundaries. A closer look at the outcrop areas will be shown in the next chapter.

Mulatto Tongue of the Mancos Shale

The Mulatto Tongue of the Mancos Shale is a wedge of marine shale that separates the Dalton Sandstone Member of the Crevasse Canyon Formation from the Gallup Sandstone in the southwest part of the basin (Ridgley, 2001). In some outcrops, particularly in the southwest, Nummedal and Molenaar (1995) suggest that the Mulatto Tongue separates the Gallup and the Tocito Sandstone Lentil of the Mancos Shale and that the Mulatto Tongue is locally sandy in some regions of the San Juan Basin. The Mulatto Tongue was observed in the outcrop studies in the southeast.

Basal Niobrara Sandstones and Tocito Sandstones of the Mancos Shale

The Basal Niobrara Sandstones and the Tocito Sandstones are both sandstone lenses above the Gallup unconformity and below the Mesaverde Group sandstones. They vary in thickness from one side of the basin to the other and are often mislabeled. The Tocito Sandstone outcrops to the west and southwest sides of the basin and is composed of bi-directional cross-bedded sandstone lenses. The Tocito is the largest oil producer in the basin. On the eastern side of the San Juan Basin, the basal lenticular sandstone has been named the Cooper Arroyo Sandstone by Landis and Dane in 1967 (Ridgley, 2001). Ridgley (2001) described it as “a Tocito-like sandstone that consists of approximately 2-3 feet of coarse-grained, heavily glauconitic sandstone”. Hedayati and Wood (2007) also noted herringbone cross-bedding and a lack of shale and burrowing in some units of the Cooper Arroyo near El Vado Reservoir suggesting a shallowing of the shelf during Cooper Arroyo time. This interpretation will be discussed in subsequent chapters of this thesis.

El Vado Sandstone Member of the Mancos Shale

The El Vado Sandstone Member of the Mancos Shale is the primary focus of this report. Its type section is located near the El Vado Reservoir (Figure 1.9) and was first described by Landis and Dane (1967). They described the El Vado as "…90 to 100 feet of interbedded sandstone and siltstone…" The sandstones are described as fine-grained, calcareous, locally rippled or cross-bedded units with sandstone being most prominent in the upper one-half of the formation and siltstones more abundant in the lower half where they are interbedded with shales (Ridgley, 2001). A more in-depth description of the type section and of outcrops in the southern part of the basin will be provided in another section of this thesis.

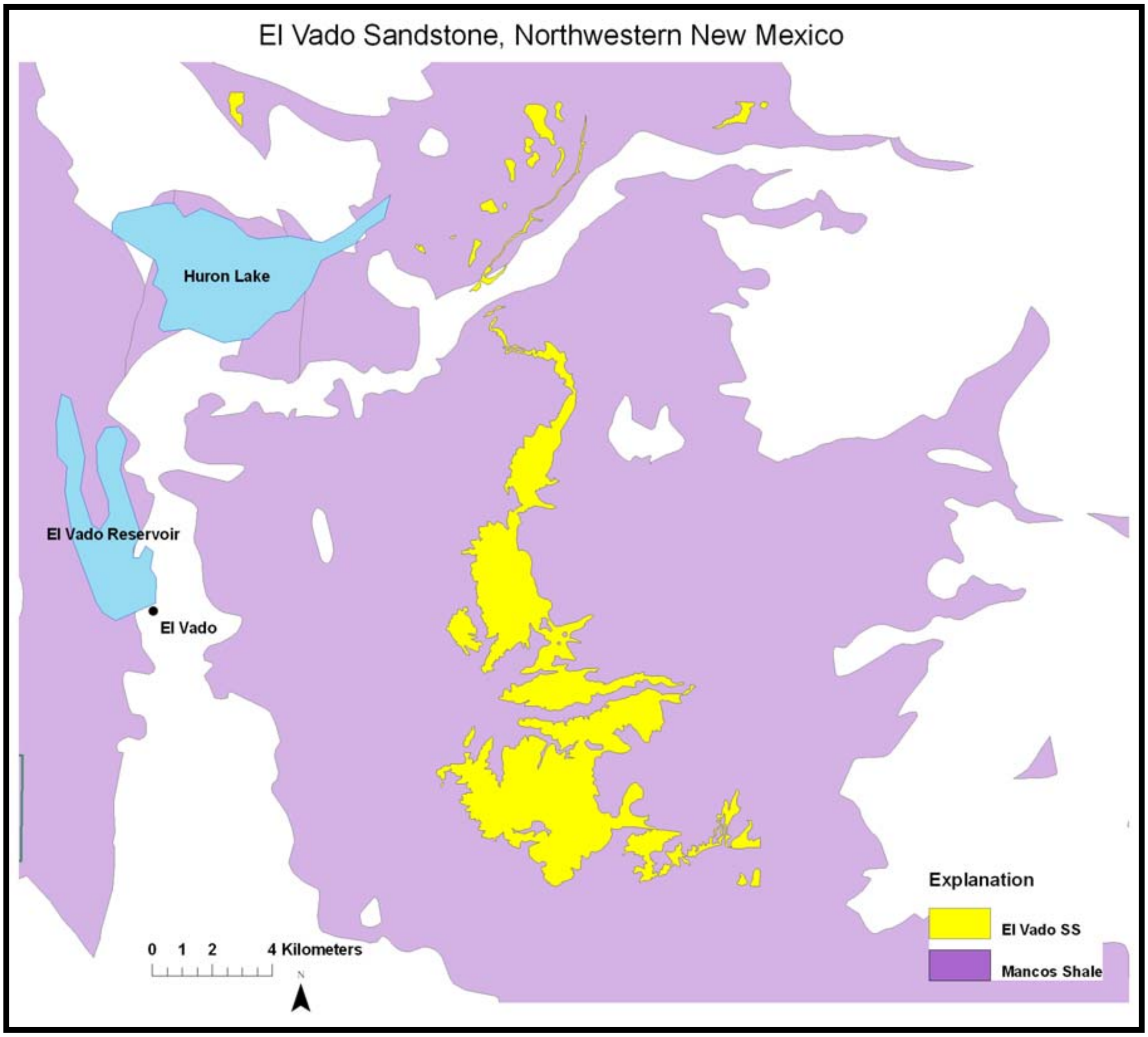


Figure 1.9: Mapped El Vado Sandstone (Landis and Dane, 1967) outcropping in northwestern New Mexico, near El Vado Reservoir.

PREVIOUS WORK

The El Vado Sandstone Member of the Mancos Shale was first described by Landis and Dane in 1967, when they authored the *Geologic Map of the Tierra Amarilla Quadrangle, Rio Arriba County, New Mexico*. This map was the first mention of the El Vado Sandstone in any published work. Through extensive field mapping, they identified the El Vado Sandstone Member of the Mancos Shale as cropping out extensively in the eastern part of the Tierra Amarilla quadrangle of New Mexico (Figure 1.9), showing it to be well exposed in the prominent westward-facing escarpments both north and south of Rio Nutrias. These authors named the El Vado Sandstone from the outcrops west of the El Vado Reservoir in the Boulder Lake quadrangle, where it makes a conspicuous low escarpment below high cliffs of the Mesaverde Group.

The El Vado type section is described by Landis and Dane (1967) as being "…90 to 100 feet of interbedded siltstone and very fine-grained sandstone, brownish to yellowish gray on fresh fractures, weathers grayish orange, some beds are harder and more calcareous, many shell fragments, beds up to an inch thick, sandier units are transitional with underlying beds but fairly sharp…". They go on to say that "…the El Vado reflects some slight local variation in the lithology of the member in exposures in the southeast part of the quadrangle, but no significant differences occur and the thickness is nearly the same between the type section and the southeast…". Their mapping remains the only field documentation of the El Vado Sandstone. Their measured section of the El Vado Sandstone can be seen in Figure 1.10. For a more complete description from Landis and Dane (1967) see the Appendix.

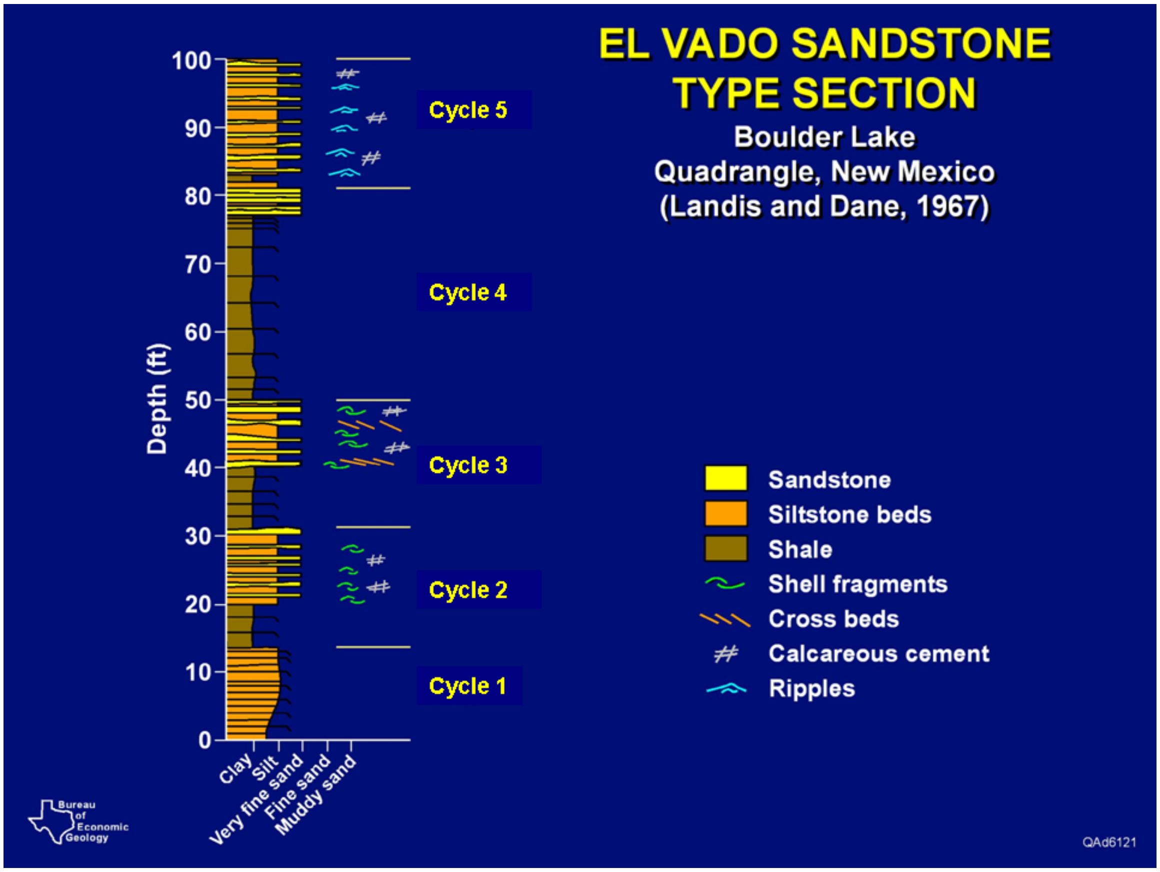


Figure 1.10: Measured section re-drafted from the description by Landis and Dane (1967) of the El Vado Sandstone type section.

Few people wrote of the El Vado Sandstone following the work of Landis and Dane (1967). However, in the late 1990's the Department of Energy funded a study of the El Vado Sandstone and the Point Lookout Sandstone, specifically in the area of the Jicarilla Apache Reservation, in northern New Mexico, which was undertaken by scientists at the U.S. Geological Survey. A report was completed by Jennie Ridgley in 2001 titled *Sequence Stratigraphic Analysis and Facies Architecture of the Cretaceous Mancos Shale on and Near the Jicarilla Apache Reservation, New Mexico - their relation to Sites of Oil Accumulation.* The goal of Ridgley's research was to define the facies of the oil-producing units within the Mancos Shale, interpret the depositional environments of these facies within a sequence stratigraphic framework, and predominantly to analysis hydrocarbon potential in the Mancos Shale on the Jicarilla Apache Indian Reservation. Her report was a comprehensive analysis of the oil bearing rocks beneath the reservation and helped raise awareness of the El Vado Sandstone as a major hydrocarbon producer in the basin.

To investigate the oil-bearing rocks, Ridgley (2001) used several types of data including, but not limited to, well logs, core, and outcrop exposures. Ridgley used 36 wells to correlate and pick formation tops throughout the basin. A total of 8 cores were logged and described for lithology, understanding of facies, and samples were taken for further rock analysis. Five cross-sections over the reservation, 2 south to north and 3 west to east, were constructed to show stratigraphic relationships between the geologic formations (Figure 1.11). Production data from the Mancos Shale interval between the Juana Lopez and the base of the Point Lookout Sandstone were extracted from a database available from IHS Energy and an evaluation of interval production was performed. Ridgley reassessed and reassigned production based upon her own observations of the formation occurrences in each well. From this data, the author could determine if there were regional production trends within certain formations on the Jicarilla Apache Reservation.

Stratigraphically, Ridgley divided the Mancos Shale into three separate units; the lower Mancos Shale, located below the regional unconformity; the middle unit, located above the unconformity and below the El Vado Sandstone; and finally the upper unit; contained the El Vado and the rest of the Mancos Shale. From the author's cross sections, the upper Mancos unit, the stratigraphic interval of the Mulatto Tongue of the Mancos (which contains both the El Vado and the Tocito) appears to be thickening northward, shown in Figure 1.12. However, the El Vado Sandstone itself appears to be a consistent thickness from north to south and the Tocito, which is stratigraphically older than the El Vado, appears to be lapping out to the south on the regional unconformity. This lapout would imply that the author believes that any Tocito Sandstones describes in the southern part of the basin would not be the same sand unit underneath the Reservation that is referred to and being produced as the Tocito Sandstone.

Depositionally, Ridgley (2001) concluded that the El Vado Sandstone Member of the Mancos Shale was deposited as facies basinward of the lower part of the regressive Dalton Sandstone. She also concluded that these El Vado Sandstone units produced most of the oil and gas from the Mancos. In the central and southern parts of the Jicarilla Apache Reservation, the author concluded, that there were large areas that have the potential to contain oil in the El Vado Sandstone, based on the trend of the facies and structure shown in her cross sections. The author also concluded that the El Vado most likely exists in a broader portion of the San Juan Basin, to the north and to the west. However, these units remain unmapped in the subsurface (Ridgley, pers. comm., April 2007).

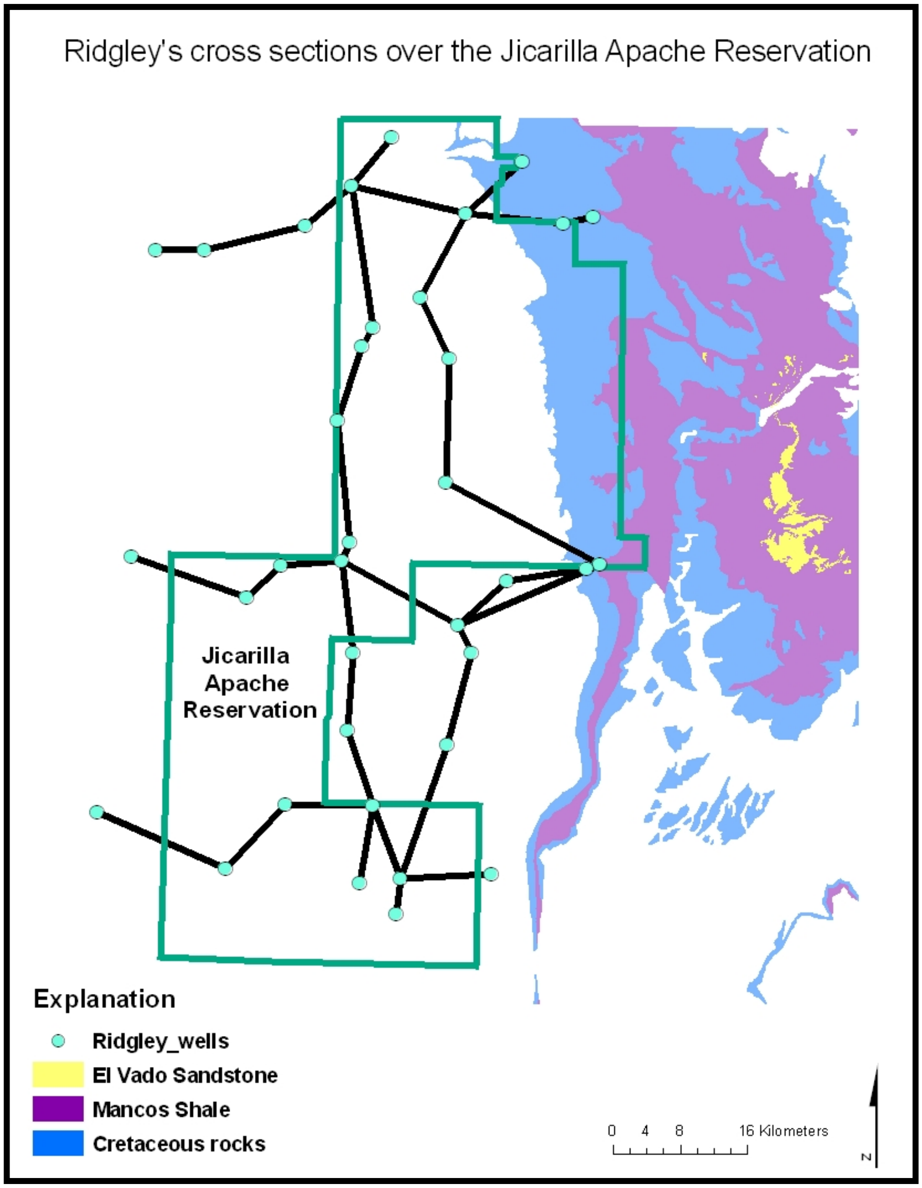


Figure 1.11: Map showing Ridgley's (2001) cross sections (solid black lines) across the Jicarilla Apache Reservation.

An examination of previous work (Jennette and Jones, 1995; Nummedal and Molenaar, 1995) and preliminary observations in the San Juan Basin have led us to ask several key questions regarding the El Vado Sandstone. Theses questions include:

(1) What is the environmental of deposition of the El Vado Sandstone interval? What is the El Vado's architecture in outcrop?

(2) What is the basin-wide distribution of the El Vado, and how does its lithology and nature change from the north to the south and from the east to the west?

(3) What is the relationship between the El Vado and the Crevasse Canyon/Dalton shoreline to the south? What is the relationship between the El Vado and the Tocito Sandstone to the west and to the south?

Answering these questions will improve understanding of the El Vado reservoirs and possibly open up new opportunity in the basin.

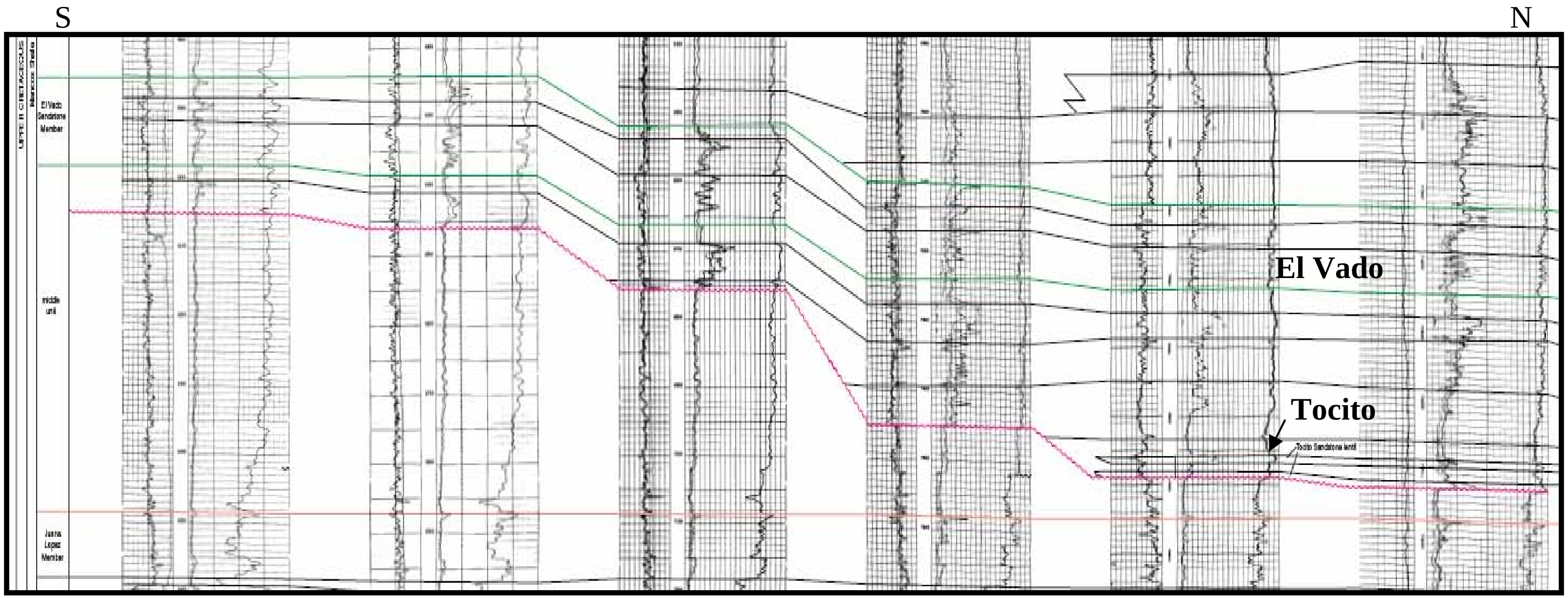


Figure 1.12: South to north cross-section constructed by Ridgley (2001) showing the Tocito lapping out and the El Vado showing consistent thickness across the Reservation. Individual wells show gamma ray and spontaneous potential logs on the left and resistivity and conductivity logs on the right and far right, respectively. This section is datum on the Juana Lopez Member (orange line). The Gallup unconformity (see discussion in text) is shown in red and the top and bottom of the El Vado interval is shown in green. Individual cycles of the Tocito and El Vado intervals are show as solid black horizontal correlation lines.

2 HYPOTHESES

The questions presented above allow us to establish two competing hypotheses regarding the origin of the El Vado units. The first hypothesis relates the El Vado Sandstone to the Tocito Sandstone. Jennette and Jones (1995) purposed that the Tocito Sandstone was deposited in an incised valley, which trended from northwest to southeast, originating somewhere northwest of the modern day western margin of the San Juan basin. It is possible that the El Vado Sandstone member of the Mancos Shale is a distal shelf facies of the Tocito (Figure 1.13). The implications of this theory would mean that the El Vado Sandstone's distribution would be associated with the valleys of the Tocito and its extent would be limited throughout the basin. The occurrence of the El Vado and its sand content would be strongly tied to the cycles of the Tocito and it would predominate near the terminus of Tocito valleys.

The second hypothesis on the origin of the El Vado Sandstone is that the El Vado is a distal shelf facies of the prograding shorelines of the Dalton Sandstone (Figure 1.14), now exposed along the southern Chaco slope, similar in orientation to its original depositional strand plain. The implications of this idea would be that the El Vado Sandstone's distribution and sand quality would be associated with the Dalton shorelines, creating a much more laterally extensive deposit whose quality might improve to the south as you approach the shoreline source. Likewise, the quality and character of the El Vado would vary proximal (south) to distal (north) in relation to its proximity to the Dalton shoreline.

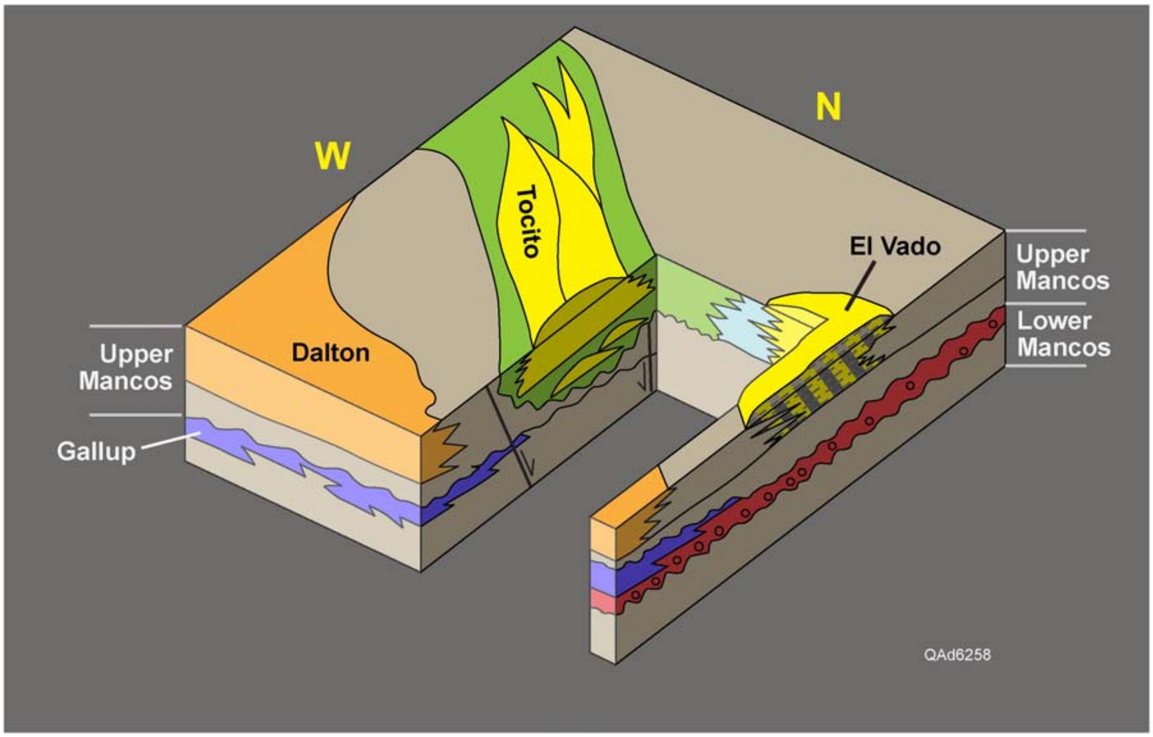


Figure 1.13: Hypothesis one; the El Vado Sandstone is a distal shelf facies of the incised valleys of the Tocito Sandstone.

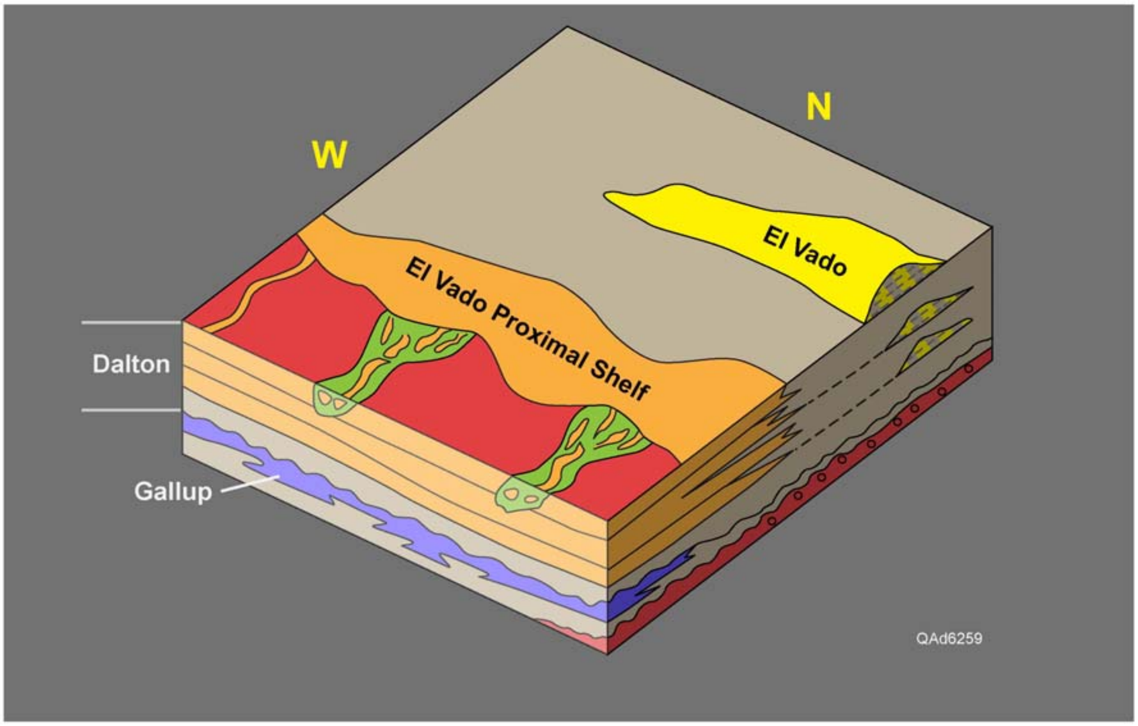


Figure 1.14: Hypothesis 2; the El Vado Sandstone if a distal shelf facies of the Dalton Shorelines.

Answering the question regarding the origin of the El Vado will lead to a much fuller understand of the distribution of Cretaceous-age shelf sediments in this important basin and possibly open up extended exploration opportunities in the El Vado through improved understanding of the updip reservoir source equivalents.

DATA AND METHODOLOGY

Over 400 raster images of well logs that penetrate and log the El Vado Sandstone and associated intervals on the Chaco Slope were downloaded from the state of New Mexico's website and then calibrated into the IHS energy software, Petra. Logging suites available consist of gamma ray (GR), spontaneous potential (SP), resistivity (RES) (shallow, medium, and deep), neutron density (NEU), and conductivity (COND). Logging suites and log quality vary depending on the age of the logs, with some wells dating back to the 1950's. Typically the GR, SP, and RES logs were depth calibrated first and then used to pick formation tops. Using depth calibrated logs, the formation top database from IHS energy, and previous work by Ridgley, new tops were assigned. Of the 400 calibrated well logs, over 200 wells logs have been assigned El Vado Sandstone intervals picked on the gamma ray or on the spontaneous potential logs. Resistivity logs were used as well to pick formation tops on a more limited basis. From the 200 well logs that had El Vado intervals, total and interval isopach maps were generated. In addition to the total thickness maps, 104 GR curves were digitized to calculate interval net sand and net-to-gross sand maps across the El Vado.

Seven northwest-southeast and six northeast-southwest cross-sections were built using available logs based on high density well control across the eastern and southeastern portions of the San Juan Basin (Figure1.15). Using the formation tops picked from cross sections, El Vado units and associated key surfaces and lithologic interpretations were tied to outcrops in the south and north of the study area (Figure 1.15). The outcrop studies provided sedimentologic and petrographic data, bed thickness, key surfaces, and stratal relationships on a much smaller scale than log derived data. Outcrops were studied both in the northern (El Vado Reservoir) and southern (Guadalupe and Cabezon Peak) locations. Samples were collected from all the outcrops and thin sections were made and analyzed. The thin sections were also stained for both calcite and dolomite to help distinguish between the two carbonate cements. The Tocito Sandstones were examined in the southern outcrops as well, although not in the same detail as the El Vado Sandstones; however samples were taken to compare and contrast against the El Vado outcrops. A scintillometer was used to gather gamma ray counts from the base to the top of the El Vado at one southern location, west of Cabezon Peak.

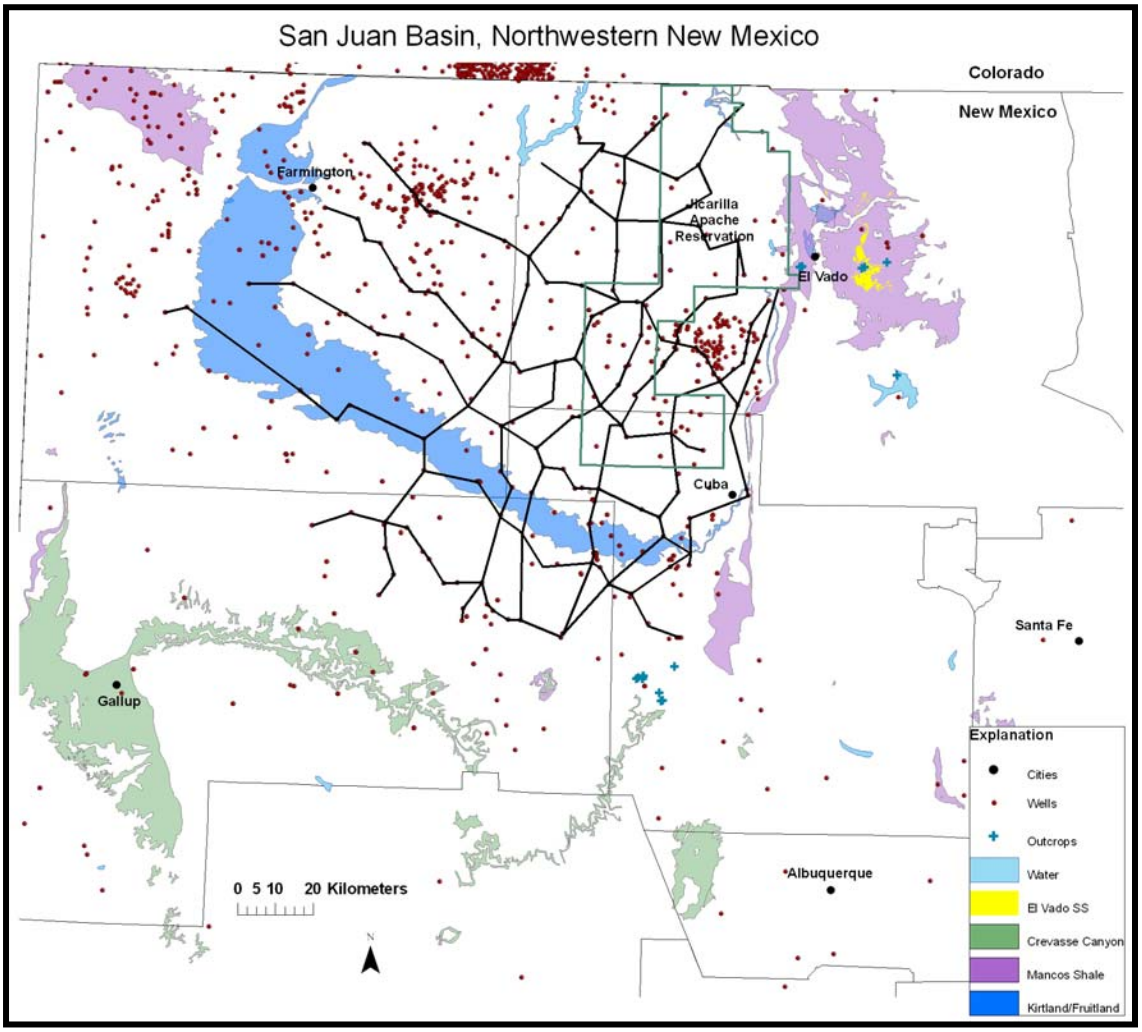


Figure 1.15: Locations of the outcrops (blue crosses) and cross sections (solid black lines) in the San Juan Basin.

Chapter 2: Outcrop Analysis

Two localities within the San Juan Basin (northeast and southeast) provided for detailed examination of the El Vado Sandstone and associated units, the Copper Arroyo Sandstone and the Tocito Sandstone. The northern locality is located near the El Vado Reservoir and the southern locality is near the volcanic neck of Cabezon Peak (Figure 2.1). Both localities were logged and described, samples taken, and thin sections were analyzed.

NORTHERN OUTCROPS

Cooper Arroyo Sandstone

The Cooper Arroyo Sandstone sits approximately 150 to 180 feet (45 to 55 m) below the El Vado Sandstones near the El Vado Reservoir (Landis and Dane, 1967). The sandstone is about 2 to 3 feet (~1 m) thick and is coarse-to-medium-grained, well-sorted in certain beds, and heavily glauconitic. Hedayati and Wood (2007) observed bi-directional cross-bedding as well as trough cross-beds in the Cooper Arroyo outcrops (Figure 2.2). The units also showed a distinct lack of shale and very limited bioturbation. Thin sections were created from samples taken from the unit and show abundant quartz grains with very minor calcite cement (Figure 2.3). This sample of the Cooper Arroyo was classified as a sublitharenite, similar to the El Vado sands; however the Cooper Arroyo contains more feldspars than the El Vado. Grains in the Cooper Arroyo were sub-rounded to sub-angular with poor sorting (grain size ranged from 1mm to 0.1mm) as shown in Figure 2.3. In outcrop, there were a mix of stratigraphic units of poorly sorted grains and other that were well sorted. Thin sections of the Cooper Arroyo

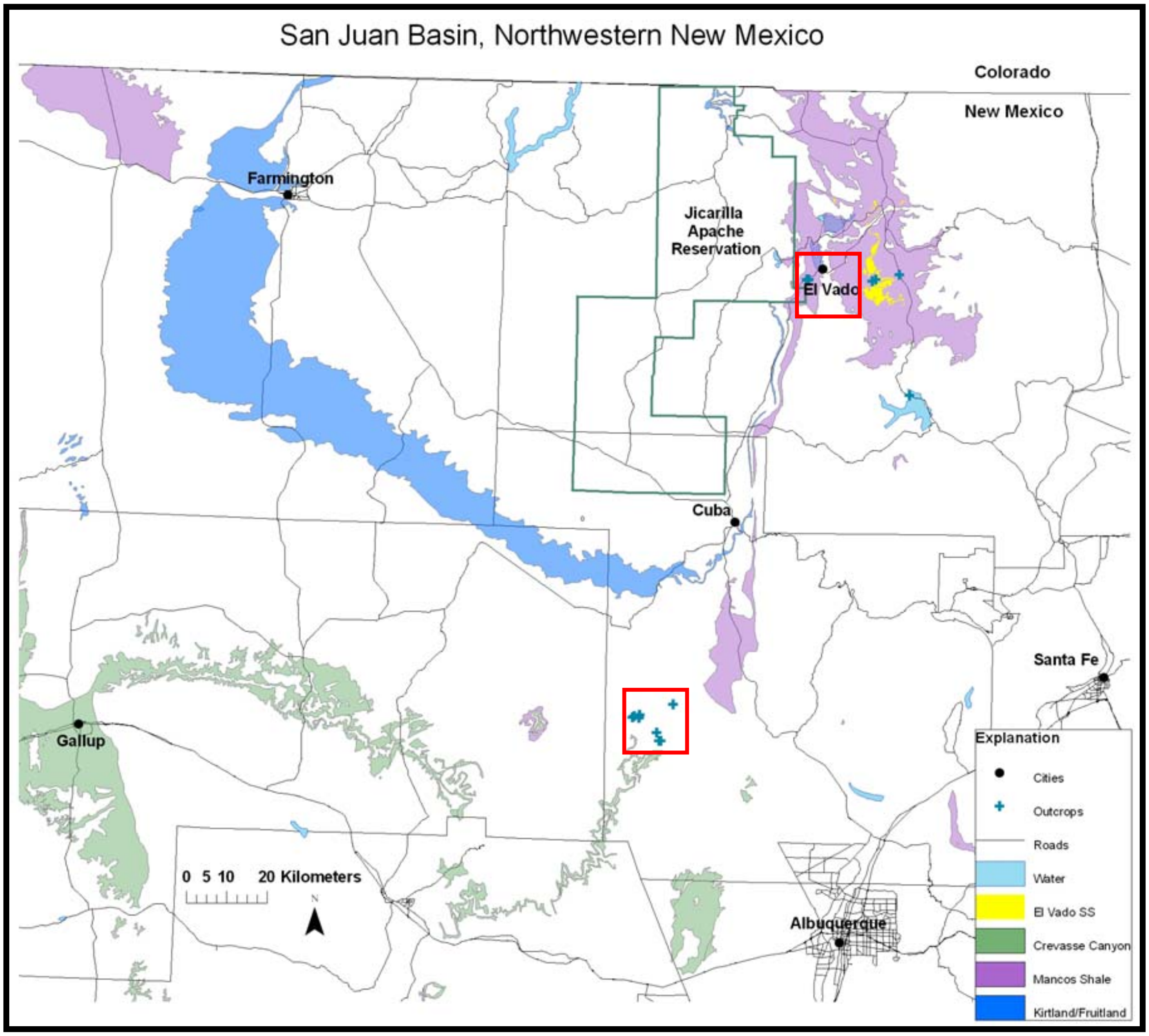


Figure 2.1: Base map of the San Juan Basin. Red boxes indicate northern and southern outcrop locations.

A

B

Figure 2.2: A.) Cooper Arroyo Sandstone displaying bi-directional cross-bedding near El Vado Reservoir. **B.)** Trough cross-bedding in the Cooper Arroyo.

A

B

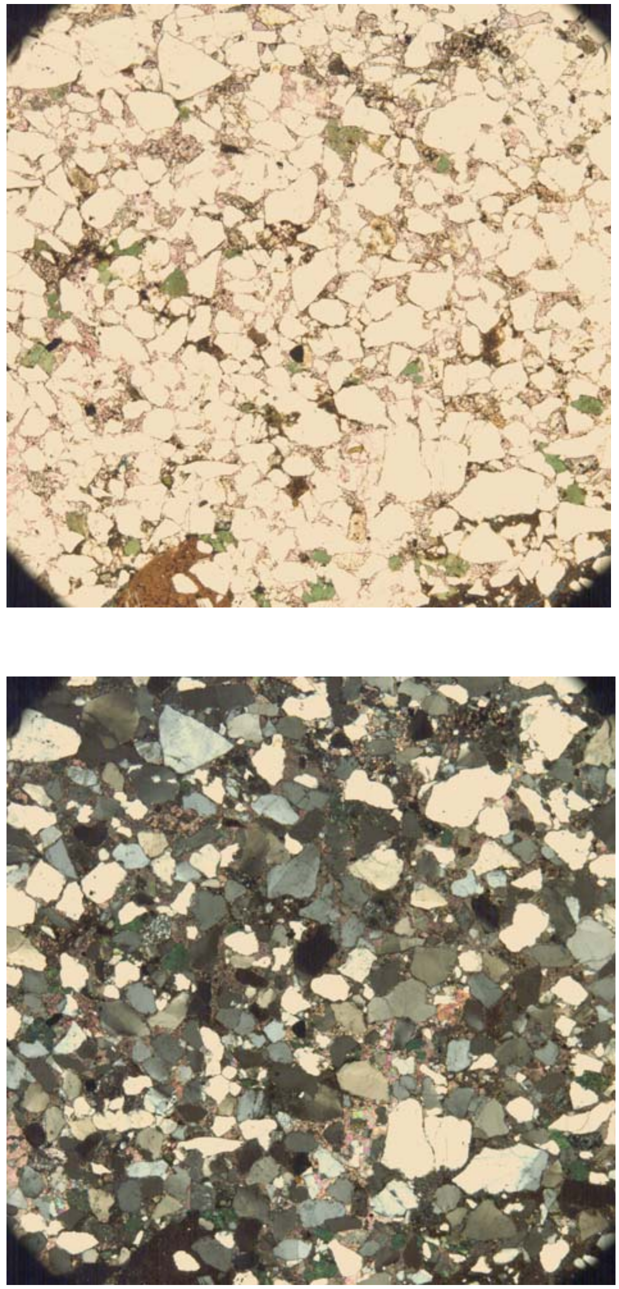


Figure 2.3: Photomicrographs of the Cooper Arroyo Sandstone displaying dominantly quartz grains and glauconite (field of view 6.5mm). **A.)** Plane polarized light. **B.)** Cross polarized light.

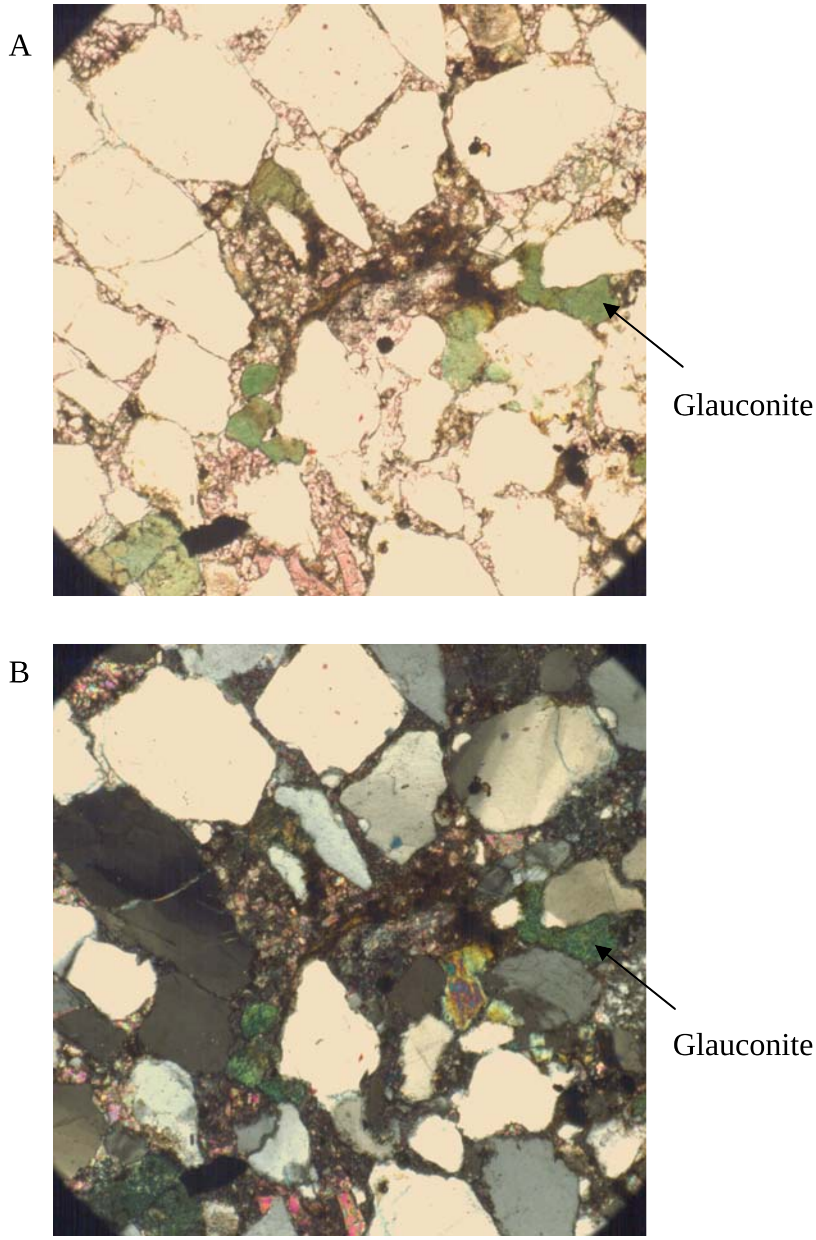


Figure 2.4: Photomicrographs of the Cooper Arroyo Sandstone displaying sub-round to sub-angular quartz grains, poor sorting, and glauconite (field of view 1.5mm). **A.)** Plane polarized light. **B.)** Cross polarized light.

showed an abundant amount of glauconite throughout the sample, with glauconite visible to the naked eye in hand samples (Figure 2.4).

Interpretation of the Cooper Arroyo near the El Vado Reservoir

The Cooper Arroyo Sandstone is described by other authors as "...a Tocito-like sand…" (Ridgley, 2001). It is possible that the unit is a lowstand shelf sand that has been "cleaned up" through reworking during transgression with a lack of bioturbation. Walker and Bergman (1993) infer that the glauconite within the Shannon Sandstone originated at shelf depths, but was reworked. Alternatively, Swift and Parsons (1999) view glauconite within the Shannon Sandstone as originating in a shelf setting concurrently with the development of the sand ridge. However because the Cooper Arroyo is so thin with limited exposure, it is hard to be definitive about the depositional environment.

El Vado Sandstone, El Vado Reservior locality

The type section of the El Vado Sandstone is located near the El Vado Reservoir on the Boulder Lake Quadrangle (Figure 2.5). It was first described by Landis and Dane (1967). At this locality, the El Vado Sandstone is approximately 100 feet thick and is comprised of 4 to 5 stratigraphic cycles (Figure 2.6). The individual cycles are highly interbedded very fine-grained sandstones and siltstone interlaminated with shale units. Thickness of individual laminae varies. The sand content appears to increases as you move up the section and each individual cycle becomes progressively sandier than the cycle beneath it. The cycles are sharp based but non-erosional (Figure 2.6). The sharp base appears to be caused by a change in the percent sand across the basal boundary each cycle.

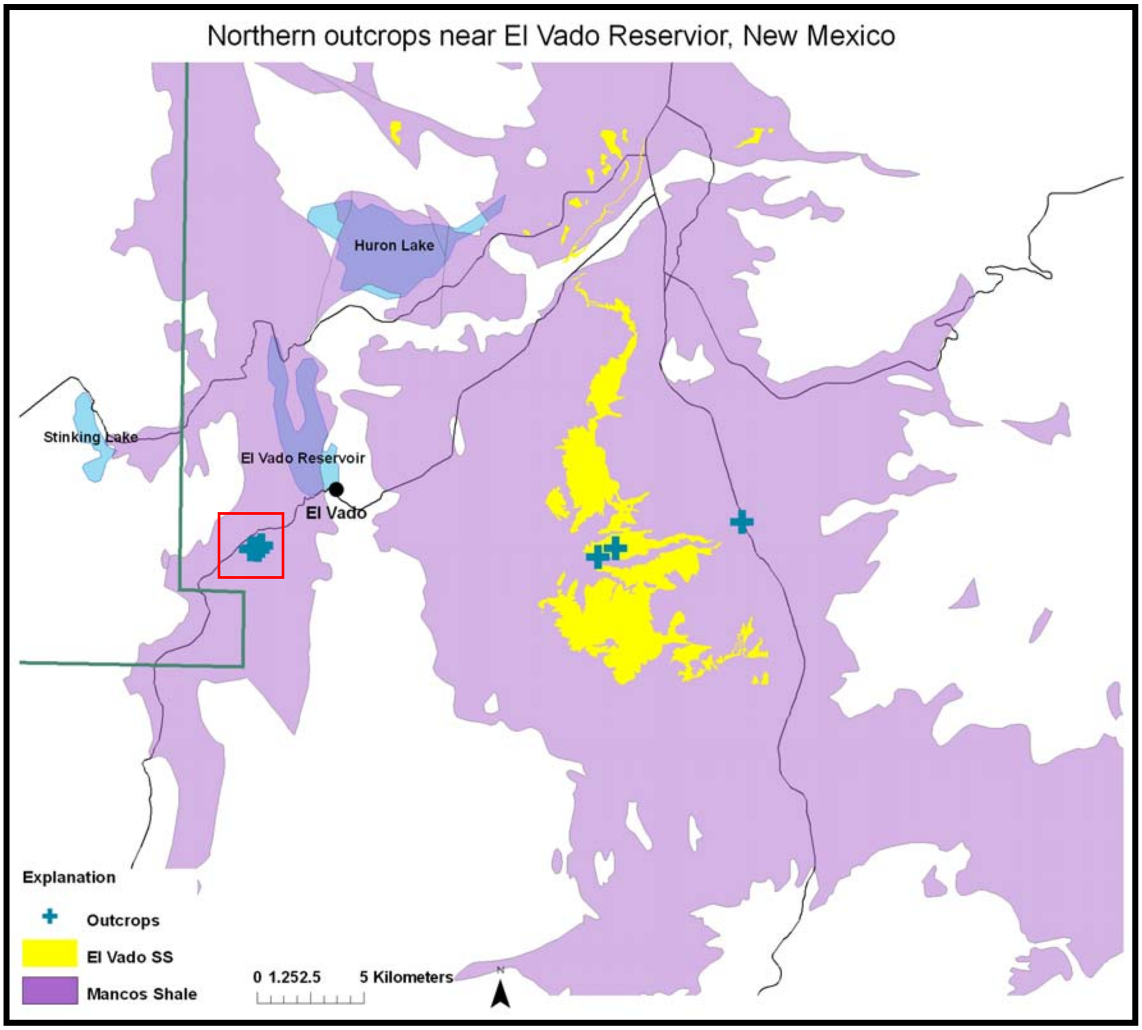


Figure 2.5: Outcrops located near the El Vado Reservoir were described and logged (red box outlines outcrops).

Figure 2.6: Outcrop of the El Vado Sandstone near the El Vado Reservoir (red circle shows the author for scale).

Cycles all show abundant shell fragments, trace fossils, and some small scale ripple cross-laminations. Thin sections of samples collected throughout the El Vado Sandstone interval show abundant calcareous cement. However individual cycles do show some unique features in outcrop, as discussed below.

Cycle 1

Cycle 1, the stratigraphically lowest cycle, contains predominantly siltstones and silty shales in beds of less than a centimeter to a couple of centimeters in thickness (Landis and Dane, 1967). This cycle is difficult to access in outcrop, forming steep inclines and cliff faces and tends to be often covered by talus and vegetation. Therefore, the description from Landis and Dane was used to describe this cycle which is approximately 14 feet thick (~4 m). Landis and Dane did not note any ripples or shell fragments in this cycle nor did they note the presence of calcareous cement. Above cycle one, there is about 6 feet (~2 m) of shale that makes a recessive notch in the outcrop and this is overlain by Cycle 2.

Cycle 2

Cycle 2 comprises 11 feet (~3 m) of interbedded very fine-grained sandstones and siltstones (Landis and Dane, 1967). This cycle is also partially covered by talus, but it is sandier than Cycle 1, and forms a resistive ledge that is easy to trace along the outcrop. The base of Cycle 2 is fairly sharp, but most of the basal contact is covered by silt and is not visible. Landis and Dane noted many shell fragments as well as calcareous cement in this sand unit. Cycle 2 is sharply overlain by ~ 9 feet (~3 m) of shale, which is in turn sharply overlain by Cycle 3.

Cycle 3

Cycle 3 is approximately 10 feet (~ 3 m) thick and contains thin bedded very fine-grained sandstones and siltstones (Landis and Dane, 1967) (Figure 2.7). The previous authors also noted that this cycle contained abundant oyster fragments (Figure 2.8), small scale cross-bedding (Figure 2.9), and abundant trace fossils (Figure 2.10) as well as calcareous cement. Landis and Dane (1967) suggested that the cross-bedding within the Cycle 3 (Figure 2.9) "…resulted in an increase of thickness of sub-units from 1 to 2 feet (0.3 to 0.6 m) along the outcrop…". The basal contact between the sandier laminated units of Cycle 3 and the shales of the underlying units is sharp (Figure 2.7) due once again to a sharp change in percent sand. The entire Cycle 3 forms a noticeable ledge that is very easy to trace from one side of the outcrop to the other (Figure 2.11). This cycle is the blockiest and most resistive unit in the entire outcrop and its thickness appears to be uniform throughout the entire section. Fish teeth and shell hash beds were also found in this unit (Figure 2.8). Samples taken from this cycle were used to make thin sections for further analysis of the petrology. In thin section, quartz grains are predominating with few lithics (sublitharenite) (Figure 2.12). The quartz grains are sub-angular, well-sorted, and very fine-grained. The sample shows an abundance of calcite cemente, however there are fewer foraminifera and oxidized pellets (authigenic pyrite crystals) in this sample than those found in Cycle 4 and 5 (Figure 2.12). These pyrite crystals are interpreted to have formed as a replacement of organic matter and fecal pellets, both of which can be suggestive of shelf settings (Walker and James, 1992). Thin sections from Cycle 3 did not contain as many shell fragments as the thin sections taken in the overlying Cycle 4.

Figure 2.7: Cycle 3 consisting of thin bedded very fine-grained sandstones and siltstones.

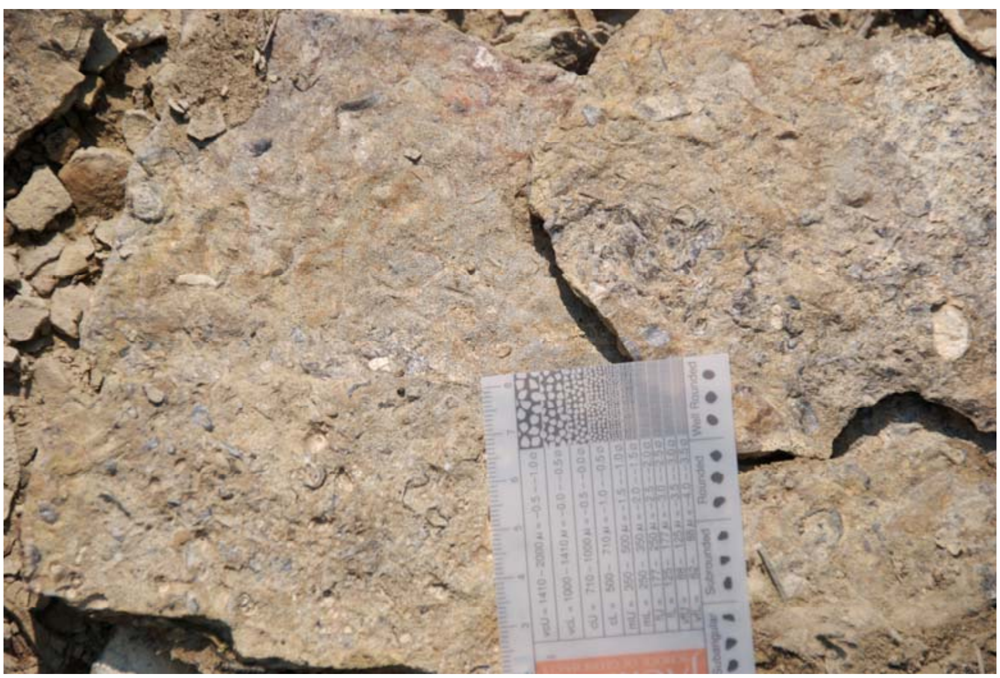


Figure 2.8: Oyster fragments and oyster shell hash within Cycle 3 (grain size card is 9 cm on its long axis).

Figure 2.9: Small scale cross-bedding in Cycle 3. Grain size card is 9 cm on its long axis.

Figure 2.10: Trace fossils found in Cycle 3, 4, and 5. Grain size card is 9 cm on its long axis.

Above Cycle 3, there is a very thick shale unit, measured by Landis and Dane (1967), 27 feet (~8 m) thick. This shale was interpreted by this author to be regionally correlatable in the subsurface and will be discussed as the Regional Shale later in this thesis.

Cycle 4 and 5

The uppermost ledge of the outcrop can be divided into two units, cycles 4 and 5 (Figure 2.6). These two cycles are separated by a thin shale unit that is less than a foot (30 cm) thick, which is laterally extensive in the outcrop and forms a distinct shale unit separating these two sandy cycles. Cycle 4 is approximately 5 feet (1.5 m) thick and is composed of very fine-grained sandstones and siltstones (Landis and Dane, 1967). Cycle 5 has the same lithology as Cycle 4 and is approximately 15 feet (~4.5 m) thick. As you move up the two cycles, the sand content is increasing and coarsening up with fine-grained benches (approximately 3 to 4 inches thick) capping Cycle 5. The uppermost units in Cycle 5 are platy, fine-grained 1 to 2 inch (2 to 5 cm) beds containing trace fossils (Figure 2.10). Current ripples were also noted in these units by both Landis and Dane (1967) and Hedayati and Wood (2007).

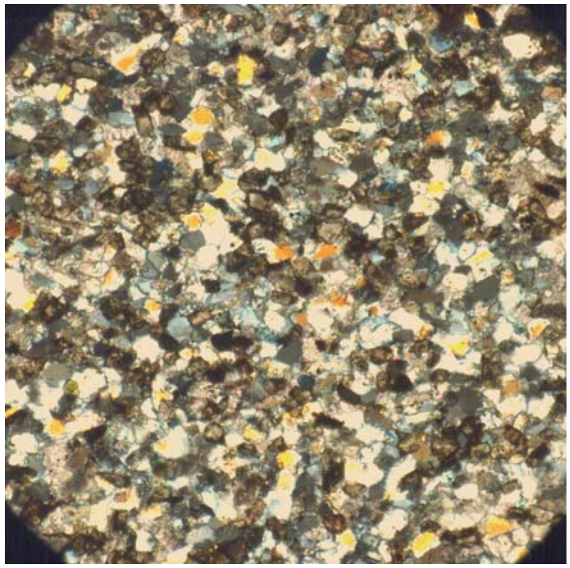
The abundant oyster shell hash found throughout the El Vado Sandstone, especially along flooding surfaces is likely the source of the calcareous cement found in the thin sections and collected samples. Photomicrographs from Cycle 5 show that like the other cycles, quartz is the dominant grain and the samples are heavily cemented by calcite and dolomite (Figure 2.13). Each thin section was stained for both calcite and dolomite; however the process was inconclusive regarding differentiation of minerals, making it difficult to tell what percentage of the thin section is calcite or dolomite. However, it is obvious that both minerals are present in the northern localities. The thin section from Cycle 5 was comprised of mostly quartz grains (sublitharenite) that are sub-angular to sub-rounded, grain size ranging from .05mm and smaller and very well sorted (Figure 2.13). The thin sections showed abundant shell fragments, oxidized pellets, and foraminifera all heavily cemented by both calcite and dolomite (Figure 2.13).

Interpretation of the El Vado near El Vado Reservoir

The El Vado Sandstone Member of the Mancos Shale in outcrops along the northeast side of the basin appears to be sheet-like and homogeneous in thickness. These sands have been interpreted to have been deposited well out in the basin in a shelfal setting. The environment of deposition of shelf sands remains very controversial. Tillman (1999) described similar outcrops to the El Vado Sandstone and classifies them as his “Inter-Ridge Shaley Facies” which he believes were deposited in an open-bay or estuarine setting. However, Dalrymple (1992) stated that estuarine ridges fine upwards, whereas active shelf ridges coarsen upwards, and that estuarine sands likely contain more mud in the form of mud drapes than shelf sands. Mud drapes were not noted by the author or by previous authors and the El Vado appear to be coarsening upward. Dalrymple (1992) goes on to describe regressive shelves as being bioturbated muds and sands transitioning into sandier sections and finally capped by cross-bedded fine-grained sands. Another interesting feature of regressive shelf units is that they are typically thicker than transgressive units and can be tens to hundreds of meters thick (Dalrymple, 1992), which is what we see at the El Vado type section.

Figure 2.11: Outcrop of the El Vado Sandstone near El Vado Reservoir. The blue line follows the top of Cycle (red circle shows the author for scale).

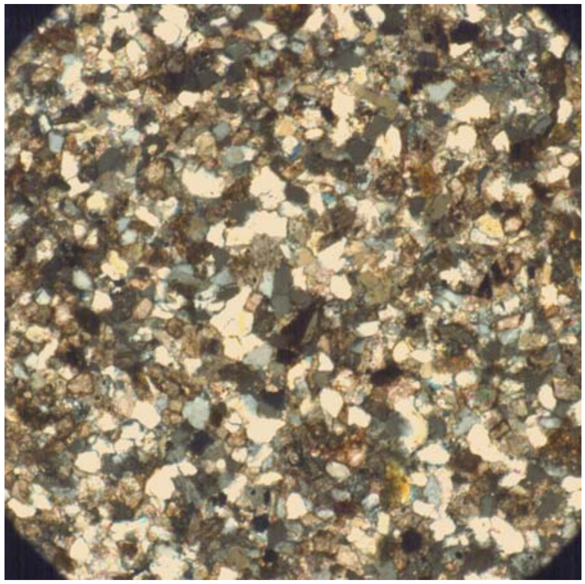
A



B

Figure 2.12: Photomicrographs under cross polarized light from Cycle 3; grains are dominantly quartz grains (note the thin section was slightly thicker than normal, causing the quartz grains to be yellow under cross polars.) **A.)** Field of view is 1.5mm across. **B.)** Field of view 6.5mm across.

A



B

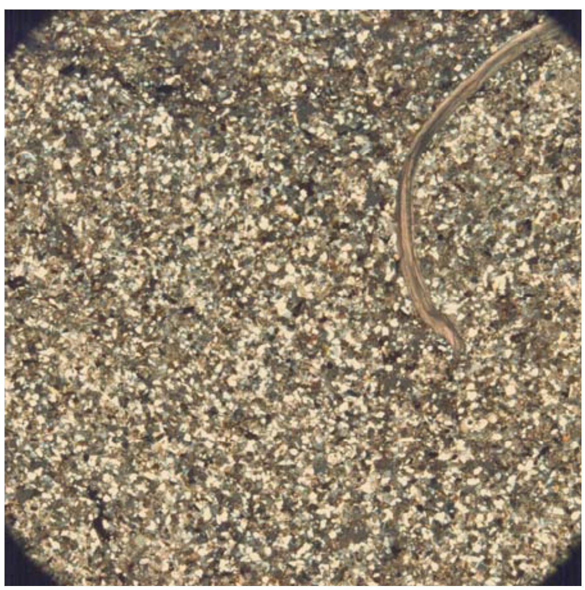


Figure 2.13: Photomicrographs under cross polarized light of Cycle 4 and 5; grains are dominantly quartz with abundant foraminifera, shell fragments, and oxidized pellets. **A.)** Field of view is 1.5mm across. **B.)** Field of view 6.5mm across; note the large shell in the photo.

SOUTHERN OUTCROPS

The outcrops in the southeast side of the basin are located near Cabezon Peak and the old village of Guadalupe (Figure 2.14). The Tocito Sandstone, which stratigraphically underlies the El Vado, has been described at several localities along the southern margin of the basin. This area has been disturbed by recent volcanic activity which has caused local faulting; making stratigraphic correlations difficult at times, so caution was made to ensure the same stratigraphic horizons were being examined at these localities. Since both the El Vado and the Tocito are sandy intervals that lie above the Gallup shoreface, it was important to locate and examine the Tocito to ensure we were not confusing this unit with the younger El Vado Sandstone sequence, the Tocito was examined near the Village of Guadalupe.

Tocito Sandstone, Guadalupe Village locality

The Guadalupe outcrop was first described by Nummedal and Molenaar (1995) in their study on the Gallup shoreface. They described what they interpreted to be Tocito Sandstone lentils separated from the Gallup Sandstone by the Mulatto Tongue. The outcrop was not described in detail but the authors did publish a schematic measured section showing their interpretation of the relationship between the Tocito and the Gallup (Figure 2.15). For this study, the Tocito was examined at the Guadalupe Village locality to assess the character of the Tocito in relation to the observed character of the El Vado in outcrop. The Tocito Sandstone at Guadalupe Village was approximately 20 feet (~6 m) thick with two obvious sub-units. The lower sub-unit, a medium-to-fine-grained sandstone with abundant shell fragments (some in large concretions) and some small scale cross-bedding, made up the bulk of the outcrop (Figure 2.16). The upper sub-unit

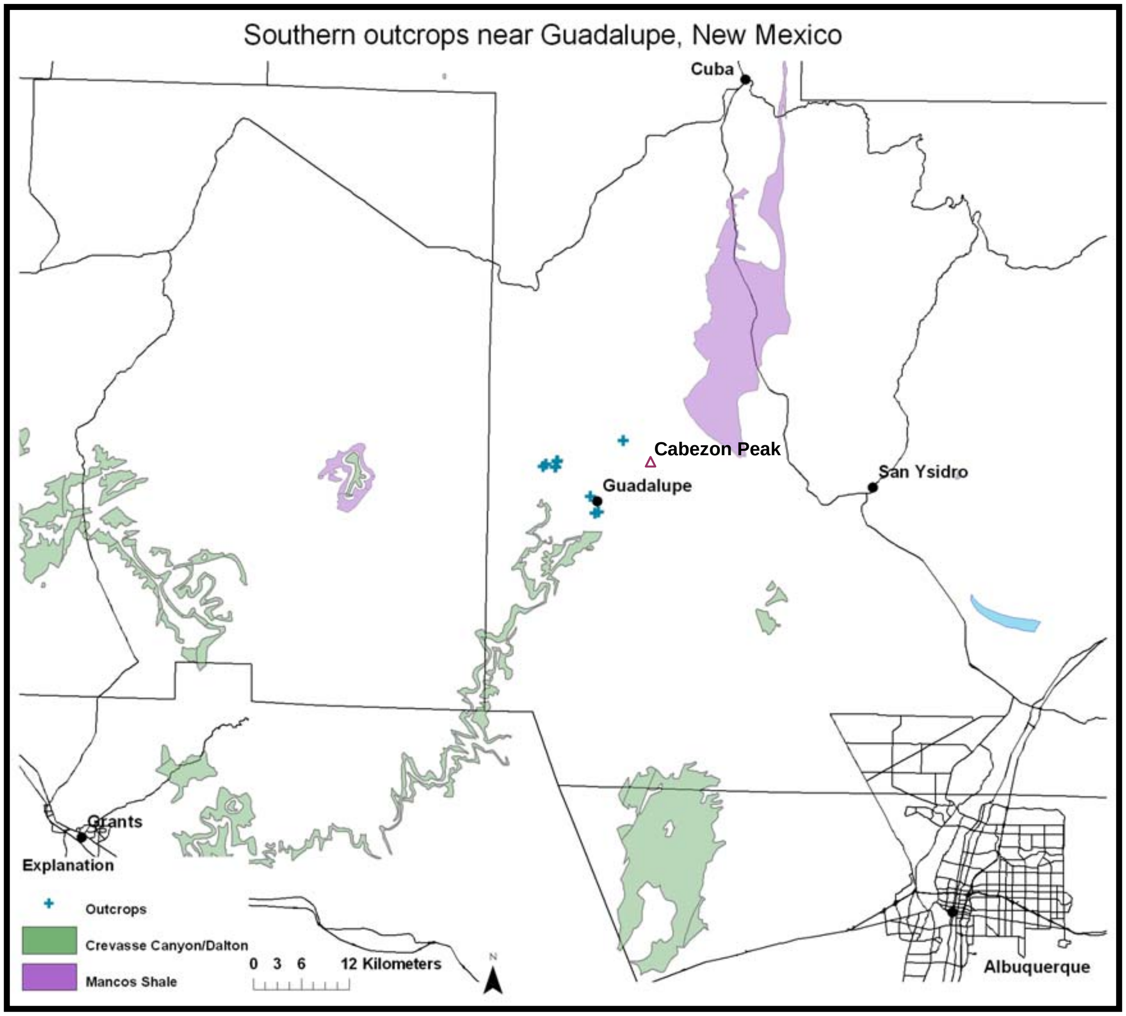


Figure 2.14: Location of the southern outcrops near Guadalupe Village and Cabezon Peak. Maroon rectangle denotes Cabezon Peak.

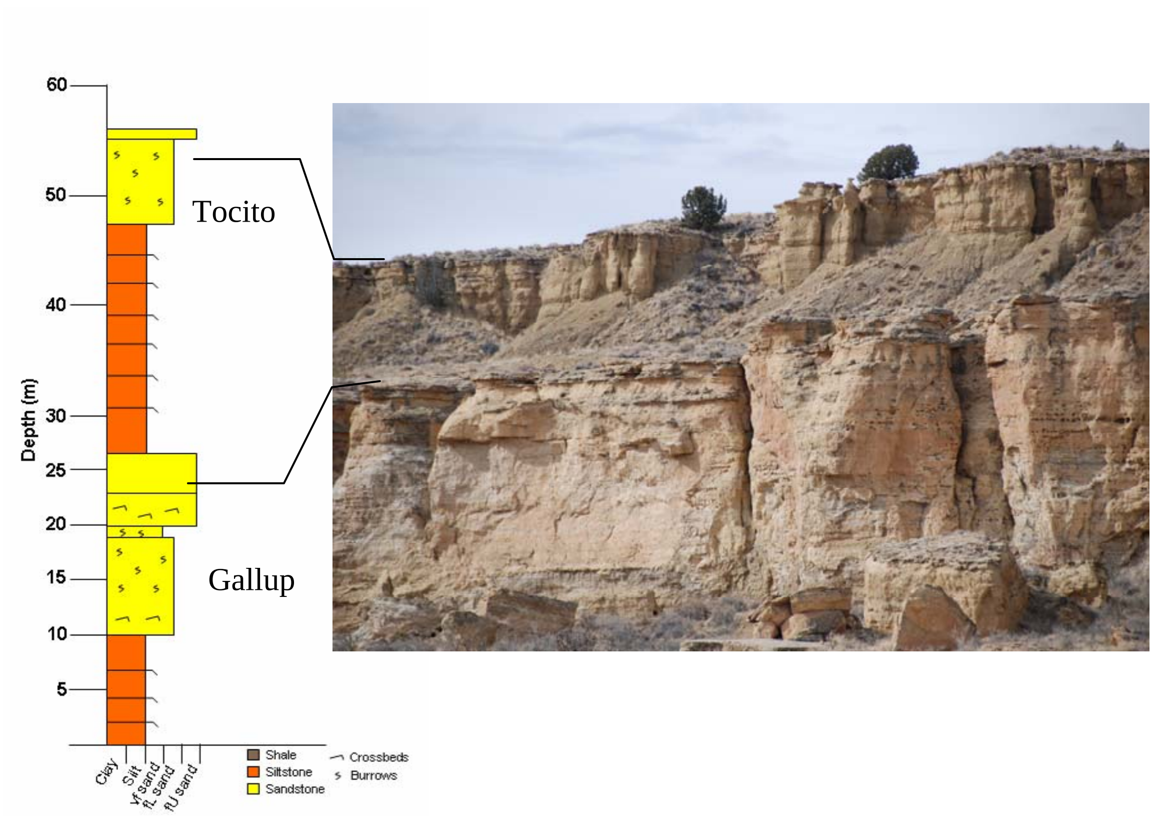


Figure 2.15: Photograph and re-drafted measured section from Nummedal and Molenaar (1995) showing the relationship of the Gallup Shoreface and the Tocito Sandstone near the Guadalupe Village.

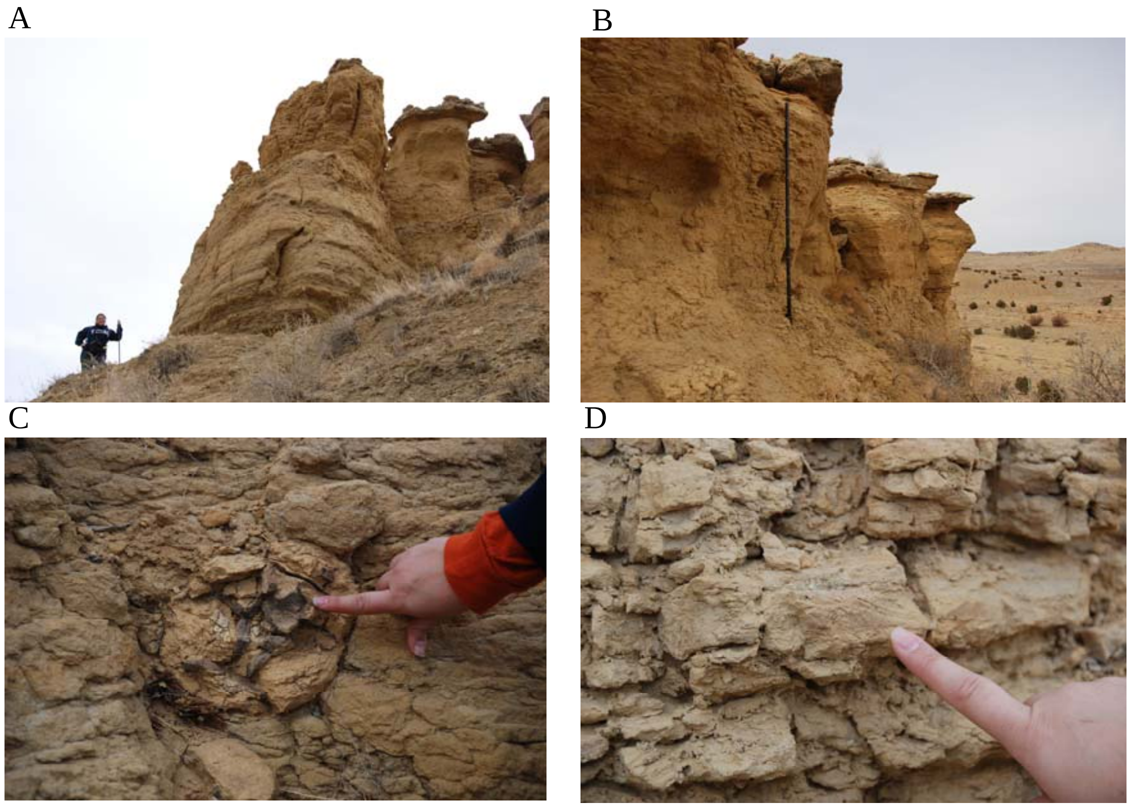


Figure 2.16: Tocito Sandstone outcrop near Guadalupe Village. **A.)** The lower and upper sub-units with the author for scale. **B.)** The top section of the lower sub-unit, note the obvious lithology change into the upper sub-unit (note 1.2 m Jacobs staff). **C.)** Shell fragments contained in a large concretion in the lower sub-unit. **D.)** Small scale cross-bedding in the lower sub-unit.

was about 2 feet (60 cm) thick and appeared to be mostly a lag deposit, which was composed of a coarse-grained sandstone that was poorly cement and very friable. Samples of both the upper and lower units were taken and made into thin sections for further analysis. The thicker, lower unit contained mostly quartz grains with a few feldspars, abundant chert fragments, micas, iron oxides (possible fecal pellets), and very minor calcite cement (Figure 2.17). The grains are sub-angular to angular and loosely packed, with roughly 5-10% porosity. The thinner, upper unit contained all quartz grains that were sub-rounded to rounded and some minor calcite cement (Figure 2.18). The grains were also fractured but no quartz overgrowths were visible. This later observation of fractures leads to the caution that such fracturing can occur by the thin section making process and may not be insitu.

Interpretation of the Tocito Sandstone at the Guadalupe Village

The Tocito Sandstone is interpreted to be a transgressive shelf deposits (Valasek, 1995; Nummedal and Riley, 1999) in this locality. The lower sub-unit has abundant shell fragments and very small scale cross-bedding which was interpreted to be a marine environment out on the shelf, with influences by tides (Nummedal and Riley, 1999). The Tocito outcrop near Guadalupe Village resembles the attributes listed by Nummedal and Riley (1999) of their “Upper member” Tocito, which they interpreted as a sand-ridge on a tide-dominated shelf. The upper sub-unit is thought to be a transgressive lag deposit because of the grain size, roundness of the grains, and size of the deposit (very thin). Walker and Plint (1992) suggest that during transgression former beach gravel can be spread out as a thin transgressive lag. I believe this to be the case of the upper Tocito sub-unit.

A

B

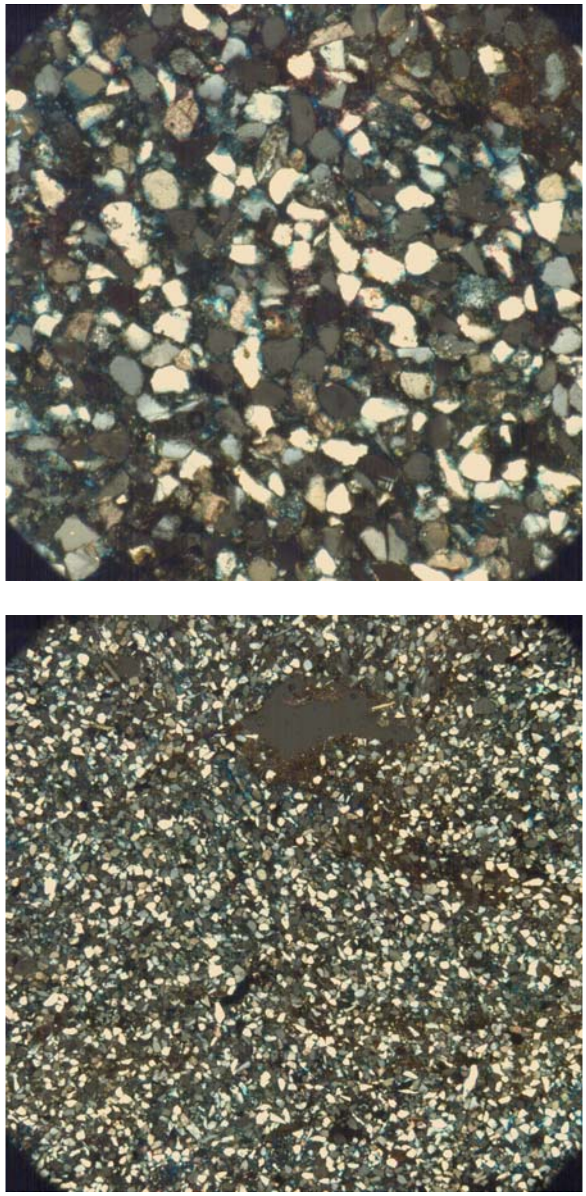
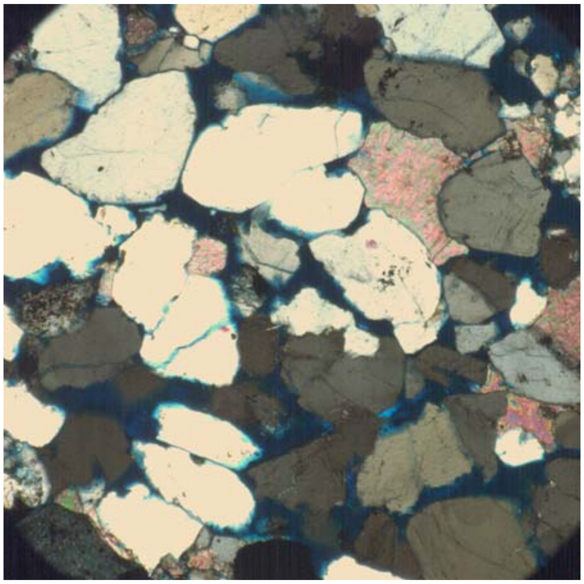


Figure 2.17: Photomicrographs of the lower sub-unit of the Tocito Sandstone near Guadalupe Village displaying mostly quartz with minor cement and loosely packed grains. **A.)** Field of view is 1.5mm across. **B.)** Field of view 6.5mm across.

A



B

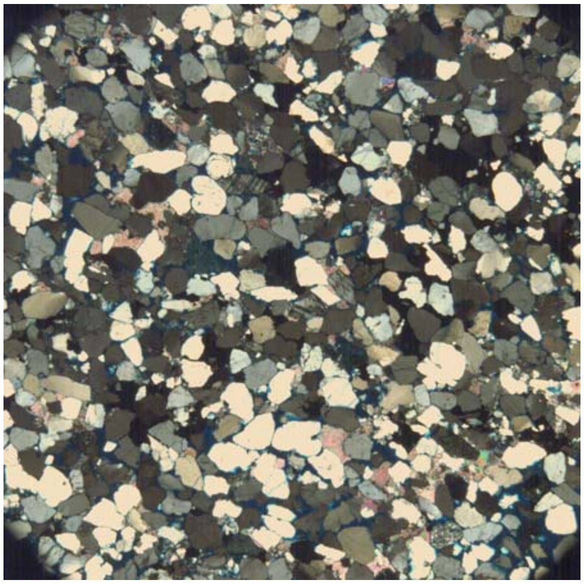


Figure 2.18: Photomicrographs of the thinner, upper sub-unit of the Tocito Sandstone near Guadalupe Village displaying rounded to sub-rounded quartz with some calcareous cement (note the size of the grains compared to the previous figure). **A.)** Field of view is 1.5mm across. **B.)** Field of view 6.5mm across.

El Vado Sandstone, Northwest of Cabezon Peak

The El Vado Sandstone was examined in the southern part of the basin in an outcrop that is located about 1.5 miles northwest of Cabezon Peak, a Tertiary volcanic neck (basaltic cliff) (Figure 2.14). This outcrop, which lies stratigraphically above the Tocito interval, is believed to be the El Vado Sandstone of the Mancos Shales and is the cliff former below the high volcanic peak (Figure 2.19). This section is approximately 30 feet (~9 m) thick. Unlike the northern outcrops, the Cabezon Peak outcrops do not appear to have any obvious internal cycles; although the facies do vary within the outcrop. These facies transitions allow one to divide the outcrop into two units, separated where the transition from shelf facies to lower shoreface facies takes place. Defined by this transition, the lower part of the section consists of siltstone with thin interbedded very fine-grained sandstones. In addition to the thin beds, there were also a few thicker sandstone beds ranging from 4 to 20 inches (~10 to 50 cm). The thicker sandstone units contained shell fragments, burrows, and some thin organic layers (Figure 2.20). The upper section of the outcrop transitions into a facies consisting of thin beds of fine-grained, very fine-grained, and siltstones. These thin beds range from 10 to 20 inches (~25 to 50 cm) with large burrows (Thalassinoides), ripples, and swaly cross stratification (Figure 2.21). The capping unit includes platy sands that contained swaly and hummocky cross bedding (Figure 2.21).

Interpretation of the El Vado Sandstone, Northwest of Cabezon Peak

The lower unit in this outcrop is considered to be shelf sands, similar in nature to the units studied in the northern outcrops. The upper unit transitions into a lower shoreface with abundant hummocky cross-stratification and large shrimp burrows

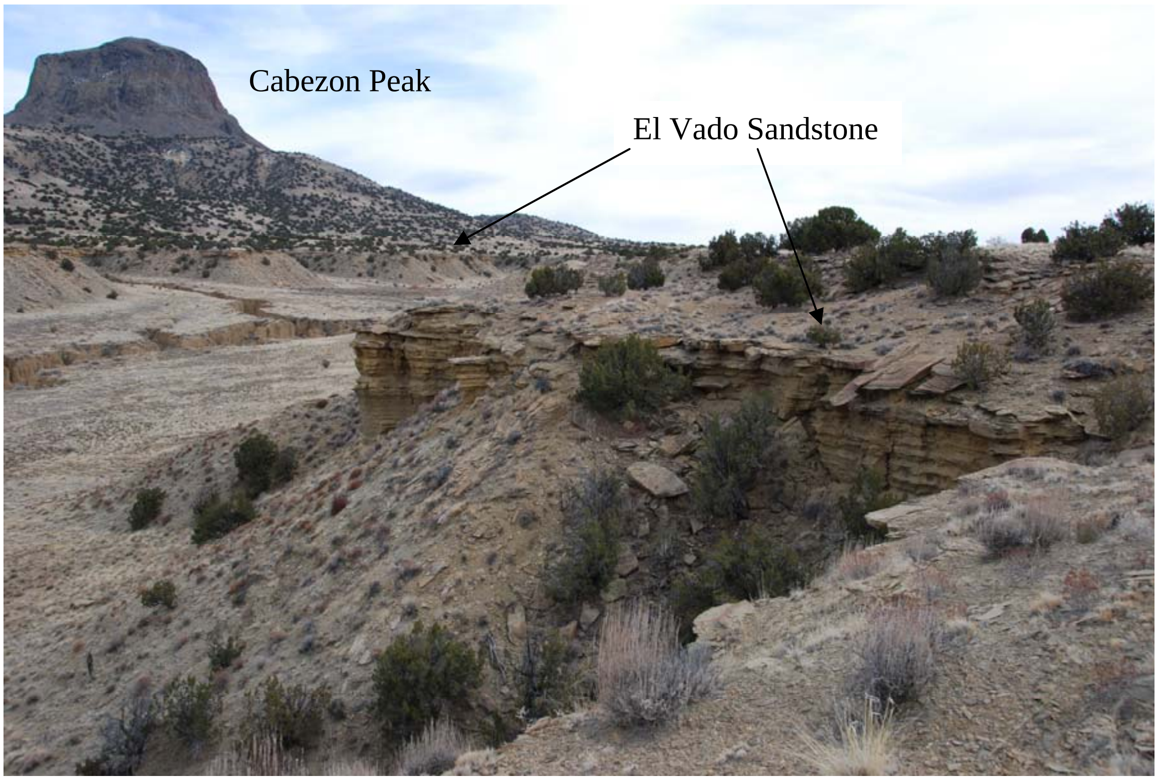


Figure 2.19: El Vado Sandstone is the cliff former below the volcanic Cabezon Peak.

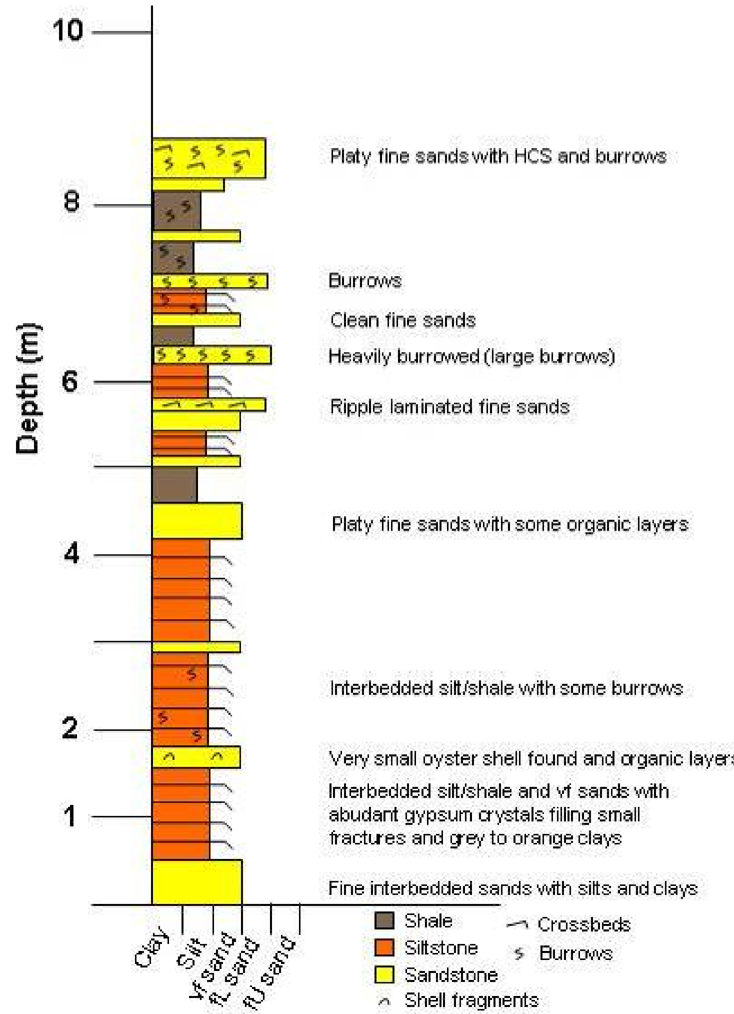


Figure 2.20: Measured section of the El Vado Sandstone located northwest of Cabezon Peak. Note the hummocky cross strata at the top of the section.

A

B

C

Figure 2.21: Features from the El Vado Sandstone located northwest of Cabezon Peak. **A.)** Burrows **B.)** Small scale hummocky cross stratification in fine sandstones **C.)** Hummocky cross stratification in fine sandstones

(Thalassinoides) (Figure 2.21), typical of lower shoreface deposits. Shoreface successions commonly have hummocky cross-stratified sandstones beneath cross-bedded upper shoreface deposits (Suter and Clifton, 1999). This statement would agree with the interpretation of the upper units are lower shoreface deposits. Another, slightly weaker, argument for lower shoreface deposits is the presence of Thalassinoides. This burrow is typically found in the Cruziana Ichnofacies, which is found in the lower shoreface to lower offshore environments (Pemberton et al., 1992).

El Vado Sandstone, West of Cabezon Peak

The third outcrop in the southeastern side of the basin was located about 6 miles west of Cabezon Peak (Figure 2.14). The El Vado Sandstone at this outcrop consists of 40 to 50 feet (~12 to 15 m) of interbedded silts and shales, with blocky fine sand layer (~10-15 inches) occurring throughout the section (Figure 2.22). At the top of the section the very fine sands are very platy and the silt/shale layers become more interbedded and finely spaced. There were a few trace fossils (burrows) found near the base of the outcrop. Samples were taken from the top of the outcrop and the base; however the majority of the remaining outcrop was inaccessible due to the steepness of the slopes. The top sand units contained mostly quartz, with not much feldspar or rock fragments (chert) (Figure 2.23). The grains were loosely packed with heavy calcite cement. The grains are angular to sub-angular, very fine-grained, and well sorted. There is more mica in samples collected from this outcrop than any of the other outcrops sampled. In addition, this outcrop showed a lack of shell fragments and foraminifera. Iron oxide pellets were observed in the thin section as well (Figure 2.23). The thin section of the bottom part of the outcrop appeared very similar to the top sands (Figure 2.24). There

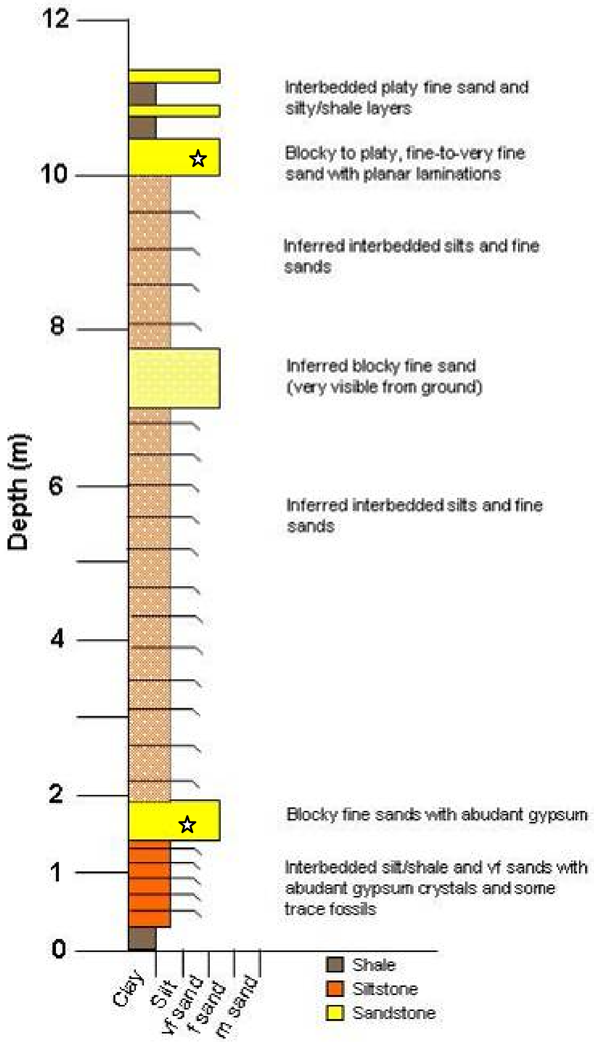
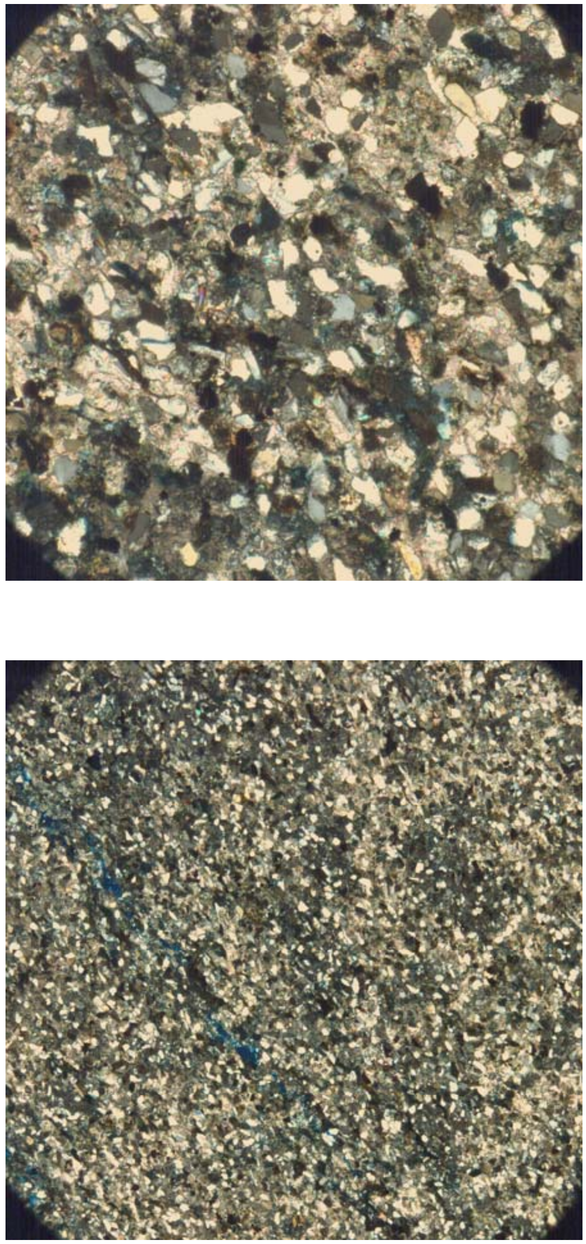


Figure 2.22: Measured section of the El Vado Sandstone located west of Cabezon Peak (note the middle part of the section is inferred because of inaccessibility). Stars on measured section indicate where samples were taken for thin sections.

A



B

Figure 2.23: Photomicrographs of the top sand from the El Vado Sandstone west of Cabezon Peak displaying very fine to fine-grained sublitharenites with abundant calcareous cement. **A.)** Field of view is 1.5mm across. **B.)** Field of view 6.5mm across.

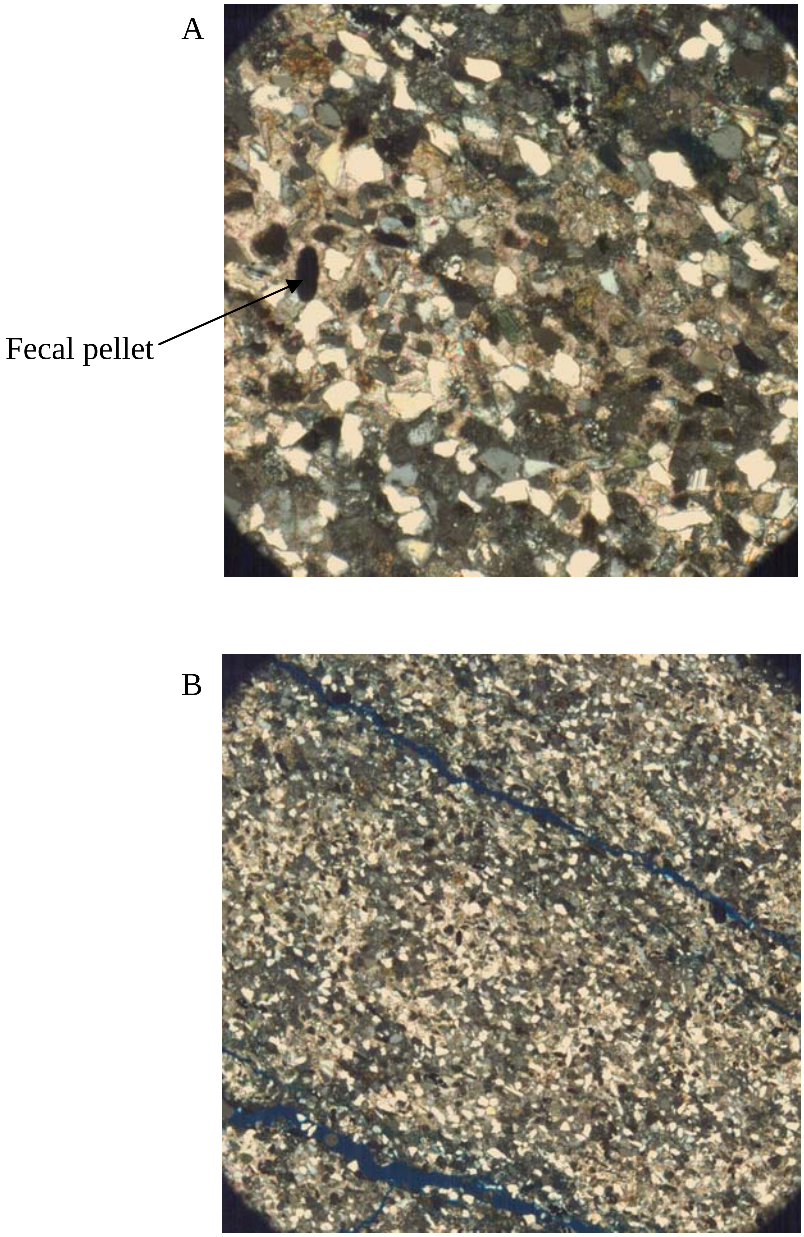


Figure 2.24: Photomicrographs of the bottom sand from the El Vado Sandstone west of Cabezon Peak displaying very fine to fine-grained sublitharenites with abundant calcareous cement. **A.)** Field of view is 1.5mm across. **B.)** Field of view 6.5mm across.

was little to no change in the petrography throughout the outcrop. The gamma ray scan from an outcrop near this one can be seen in the Appendix. The outcrop will not be discussed further because of uncertainty of how the sands correspond to the other outcrops (top and bottom are covered).

Interpretation of the El Vado Sandstone, West of Cabezon Peak

The outcrop west of Cabezon Peak is interpreted to be a shelf deposited sand body. The nature of this outcrop is very similar to the El Vado Sandstone near El Vado Reservoir. Lack of cross-beds may suggest a lower energy environment than what we see to the northwest of Cabezon Peak.

SUMMARY OF OUTCROP OBSERVATIONS

The El Vado Sandstone outcrops in the south are lower shoreface sands to shelf sands that have reached out into the basin. These sands are the proximal sand equivalents to the northern outcrops. This close proximity to the shoreline is what one would expect to see if, in fact, the El Vado Sandstones are sheet sands related to the Dalton Shoreline.

Both similarities and differences occur between outcrops of the El Vado Sandstone in the northern side of the basin and those in the southern side of the basin. The Tocito Sandstone was examined both in outcrop and petrographically to compare to the El Vado and was found to have substantial differences. The Tocito Sandstone was coarser grained, rounded to well rounded with little calcareous cement, whereas the El Vado Sandstone was found to be a finer grained, angular to sub-rounded with abundant calcareous cement.

The El Vado Sandstone outcrops in the south are interpreted to be lower shoreface sands to shelf sands that are time equivalent to the El Vado examined in the north, near El Vado Reservoir. These sands are interpreted to be the more proximal equivalents to the northern outcrops. Both intervals show a highly interbedded nature, with the units in the north broken more distinctly into progradational and retrogradational cycles due to the slightly more distal nature and thus slightly thicker flooding shales separating individual cycles. Cycles in the north lack the distinct hummocky cross-stratification seen in southern outcrops, suggesting a slightly more distal, lower shoreface setting for the entire depositional history of the northern outcrops (Walker and James, 1992).

Observations from the thin sections show little change between the northern and southern El Vado outcrops. Looking at the photomicrographs side by side, there is very little difference in lithology or sand content (Figure 2.25).

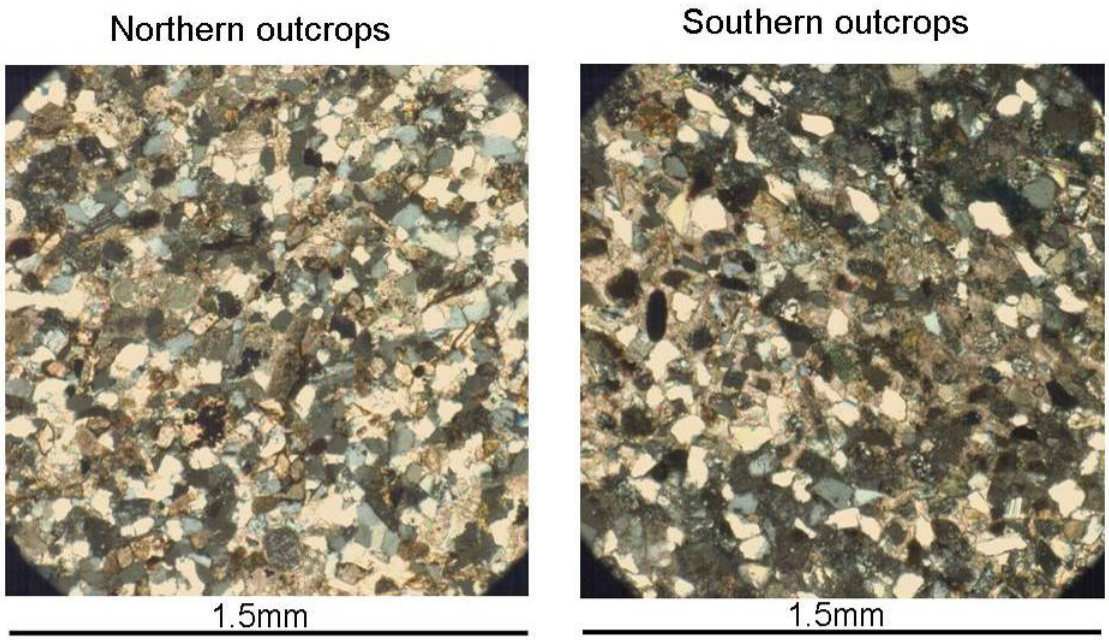


Figure 2.25: Petrographic comparison between the northern and southern outcrops of the El Vado Sandstone.

Chapter 3: Subsurface Analysis

WELL LOG ANALYSIS

Character of the El Vado Sandstone

The El Vado Sandstone is easily recognized in the subsurface on gamma ray logs as the youngest major sanding up section within the high gamma count shales of the Mancos prior to the deepest flooding of the Mancos seaway (Figure 3.1). The El Vado Sandstone interval ranges from 100 to 145 feet (30 to 44 m) thick. The generic log character of the El Vado occurs as five cycles, four dominated by progradation (regressive) and one dominated by retrogradation (transgressive) (Figure 3.2). Transgressive unit thicknesses are very limited, except for the last major transgression above Cycle 5 which is well developed and shows a slight backstepping of smaller scale cycles. The lower three cycles are clearly separated from the upper two (4 and 5) by a regionally extensive shale, as can be shown in well log cross-sections (Figure 3.4). Using this shale, the El Vado Sandstone can be broken into two cycles, the Lower El Vado and the Upper El Vado. The Lower El Vado is an over all regressive cycle. In contrast, the Upper El Vado Sandstone is composed of a regressive cycle and a dominantly transgressive cycle.

The lower three cycles of the El Vado that are displayed in well logs stack in a progradational (regressive) pattern with the entire stack overlain by a thick shale unit that is laterally continuous on a regional scale (Figure 3.4). These lowermost cycles in the gamma ray log appear to have a similar lithology and stacking pattern to those recorded in the northern outcrops, with very thinly interbedded sands and silty shales. Each cycle

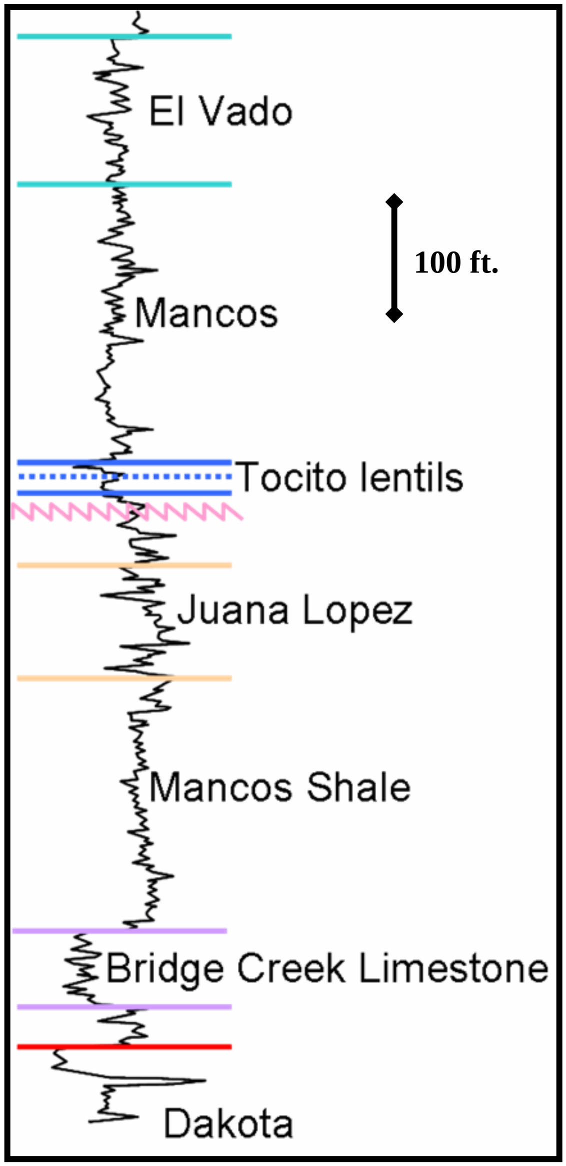


Figure 3.1: Type gamma ray log of the El Vado Sandstone and associated units. Stratigraphic units characteristic of the northeast side of the San Juan Basin are shown on the example log. Note the pink jagged line represents the regional unconformity associated with the last Gallup shoreface lowstand in the basin.

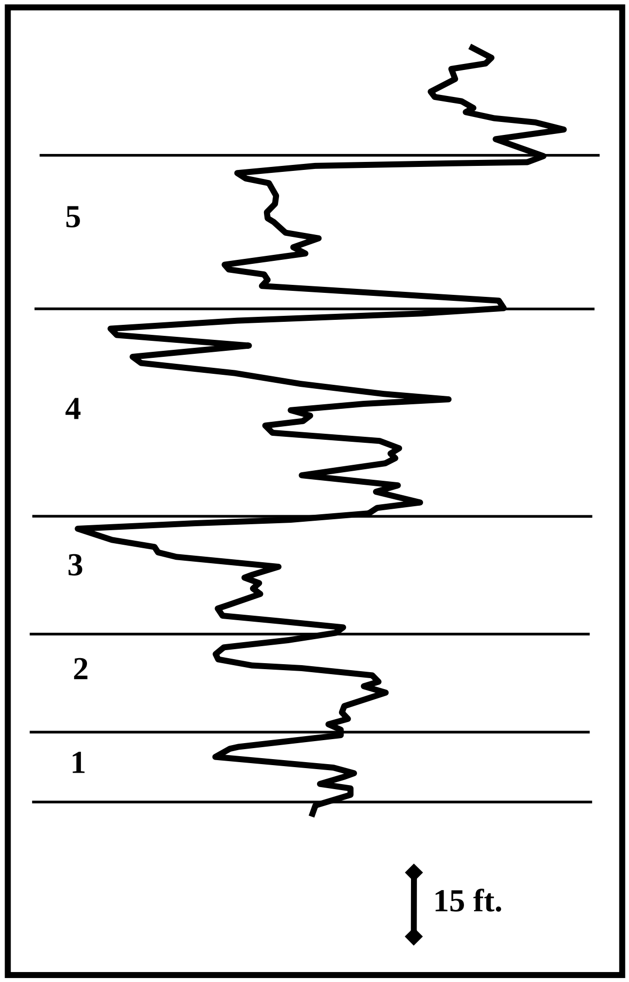


Figure 3.2: The El Vado Sandstone on a gamma ray log divided into the individual cycles. Gamma counts range from a high of 160 API (right hand side of curve) to a low of 90 API (left hand side of the curve). This curve is patterned after the Tribal-C 4-E (Consolidated Oil & Gas) well. See figure 3.3 for well location. From top to bottom of the El Vado is 120 feet.

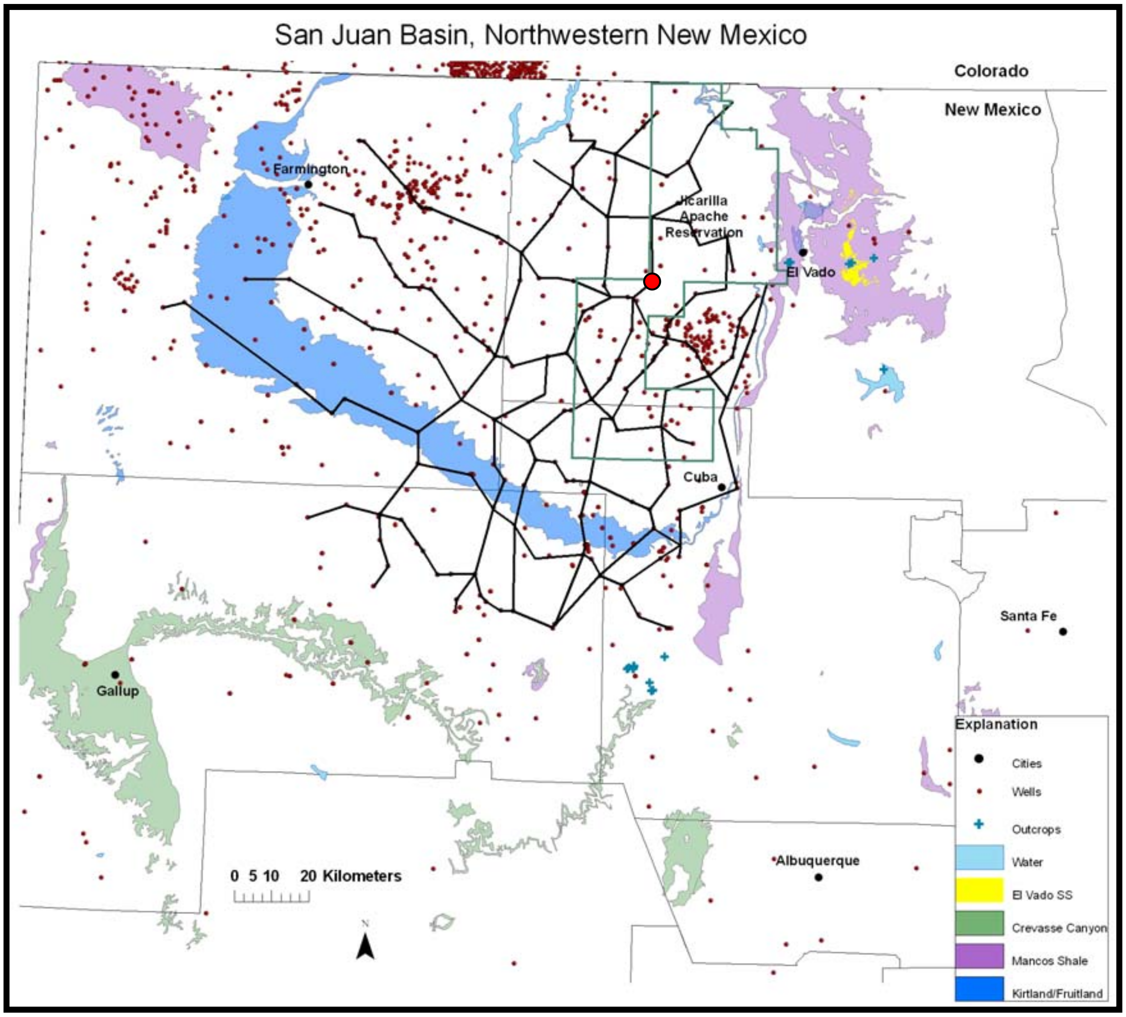


Figure 3.3: Map of the San Juan Basin displaying cross-sections created for this study. Well shown in figure 3.2 is indicated with red circle. Gray lines indicate New Mexico county boundaries.

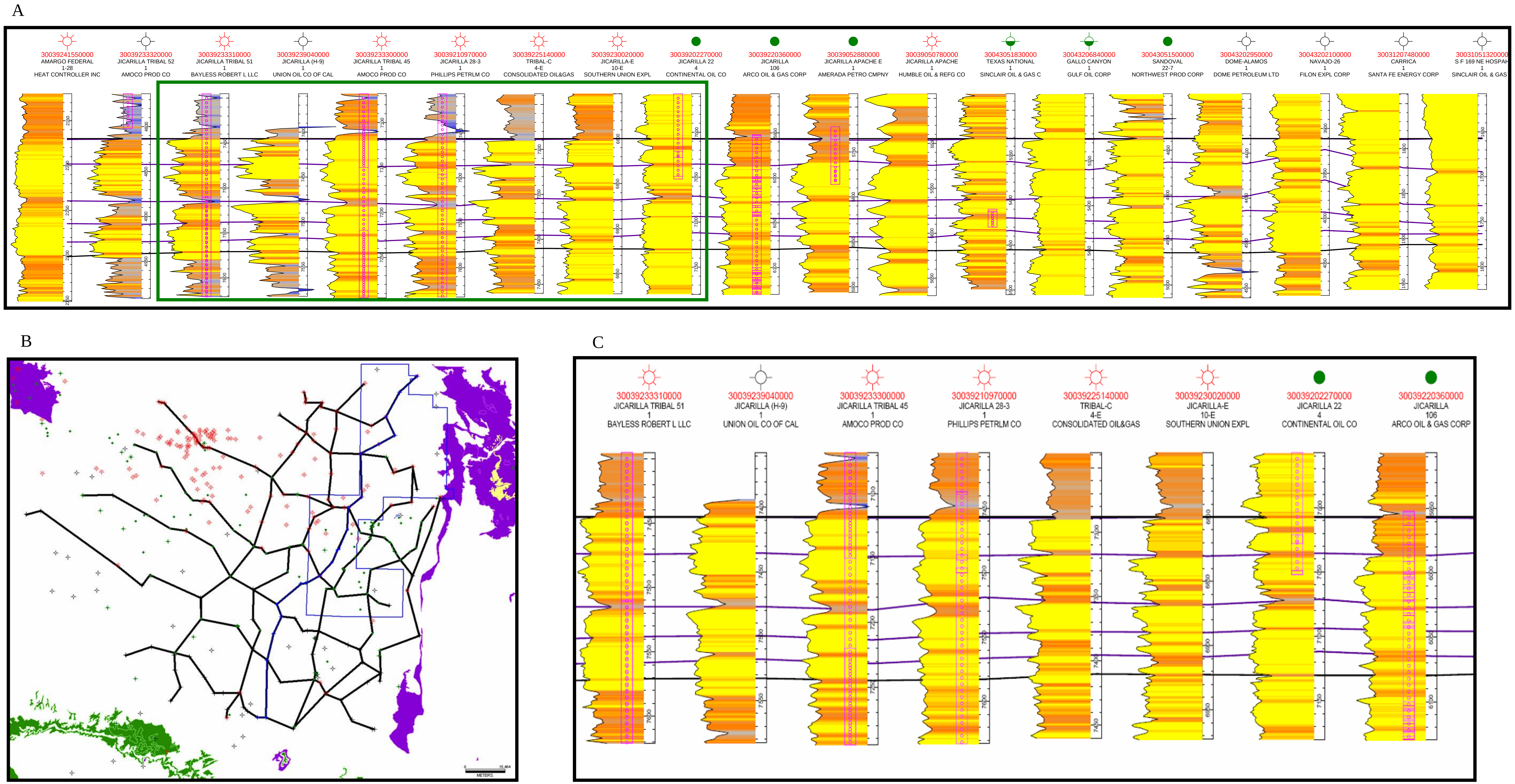


Figure 3.4: **A.)** Cross-section 4 to 4' oriented northeast-southwest (blue line). The Regional Shale is located above Cycle 3. Pink boxes indicate where the well has been perforated. **B.)** Map showing cross-sections, blue line indicates the cross-section show above. Outcrops of the Mancos are seen in purple and outcrops of the Crevasse Canyon are seen in green. **C.)** Green box in A shows location of wells.

is thickening up to cycle 3, which is capped by what the gamma ray log would indicate is a cleaner sand overlain by the Regional Shale (Figure 3.2).

The shale above the third cycle, here named the Regional Shale, has a very high gamma ray count and a low resistivity (Figure 3.2). The shale is regional in its correlatability and makes a good marker bed that separates what has been termed the Lower El Vado Sandstone from the Upper El Vado Sandstone.

The two uppermost cycles; Cycles 4 and 5, lying above the Regional Shale, are herein considered the Upper El Vado Sandstones. The fourth cycle, in well logs, is a classic "coarsening upward" sequence that is thicker than all the previous cycles. The cycle begins with shalier units and then transitions into sandy shale units. The top part of the fourth cycle is a clean sand in gamma ray logs with little appearance of high gamma ray shale beds. The fifth and final cycle of the El Vado Sandstone is dominantly retrogradational (transgressive) in character. Although the overall unit is sandier with a blockier log character than the more serrated gamma ray log motifs as seen in Cycles 1, 2 and 3 of the Lower El Vado, the entire fifth cycle shows a backstepping character which varies from subtle to dramatic.

REGIONAL CORRELATABILITY OF THE EL VADO CYCLES

Gamma ray logs from wells in the basin were used to construct seven northwest-southeast and six northeast-southwest oriented cross-sections across the study area (Figure 3.3). The goal of this work was to expand the observations of Ridgley (2001) with the intent to expand understanding of the regional extent of the El Vado Sandstone, the continuity of its cycles and assess any changes in lithologic character. Such observations would aid in understanding regional sediment source and accommodation trends. To summarize, the cross-sections show the two major cycles of the El Vado

Sandstone (Upper and Lower) continuous to the south and west of the Jicarilla Apache Reservation. However, the thickness and character of individual cycles vary. The overall thickness of the El Vado remains fairly consistent from north to south and east to west; however there is a slight thinning (~5 to 10 feet) to the southwest region of the basin. The Regional Shale is present throughout the study area. Tops were picked in each well for every cycle and were used to generate thicknesses for development of total isopach maps, and interval isopach maps, as well as provide intervals over which to assess net and percent sand maps for determining lithology distributions.

ISOPACH MAPS

Isopach maps were generated using the tops that were manually picked throughout the basin (Petra software was used in this analysis.). The total thickness isopach map was generated using all five cycles of the El Vado Sandstone and shows a thin trending north-northwest to east-southeast (Figure 3.5). The thickness of the El Vado averages 120 to 125 feet (37 to 38 m) but can range up to 110 to 140 feet (34 to 44 m). In addition to the total thickness isopach map, interval thickness isopach maps were generated to examine differences and trends in thickness of individual cycles building the El Vado Sandstone interval.

The Cycle 1 isopach map shows a fairly even thickness distribution throughout the basin, ranging from 5 to 30 feet (~2 to 9 m) but averaging 20 feet thick (6 m), with slightly thicker areas on the east-southeast and west-northwest edges of the basin. The central, thinner region is oriented northeast-southwest (Figure 3.6)

Cycle 2 shows a similar pattern to Cycle 1 with increase in the cycle thickness along the basin margins (Figure 3.7). The average thickness of Cycle 2 is slightly larger than Cycle 1, averaging 20 feet (6 m) but reaching up to 35 feet (11 m). Cycle 2 shows

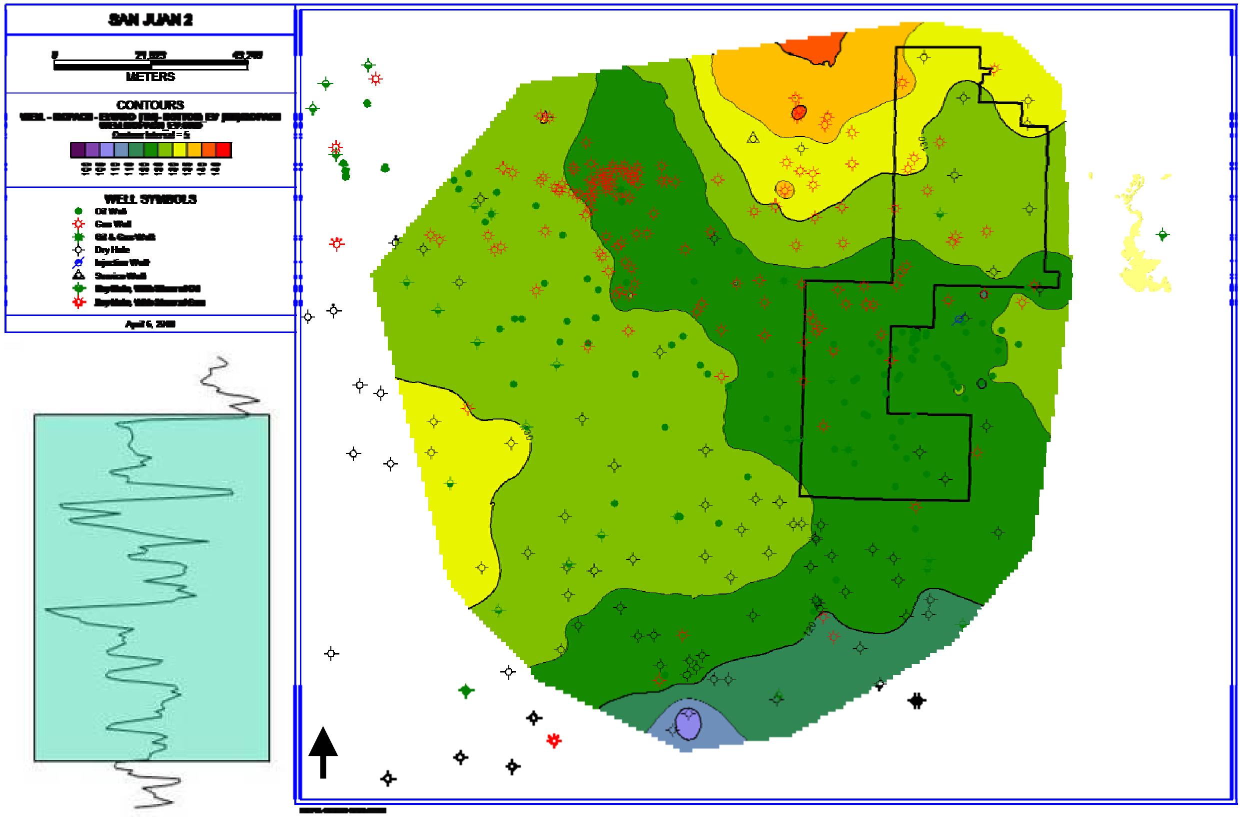


Figure 3.5: El Vado Sandstone isopach map reflecting thickness of the entire interval. The interval of thickness is shown in the green shaded log to the lower left of the map. Note the dark green thin zone trending north-northwest to south-southeast across the center of the study area. Color scale from 100 to 145 feet (left to right respectively) with 5 feet increments.

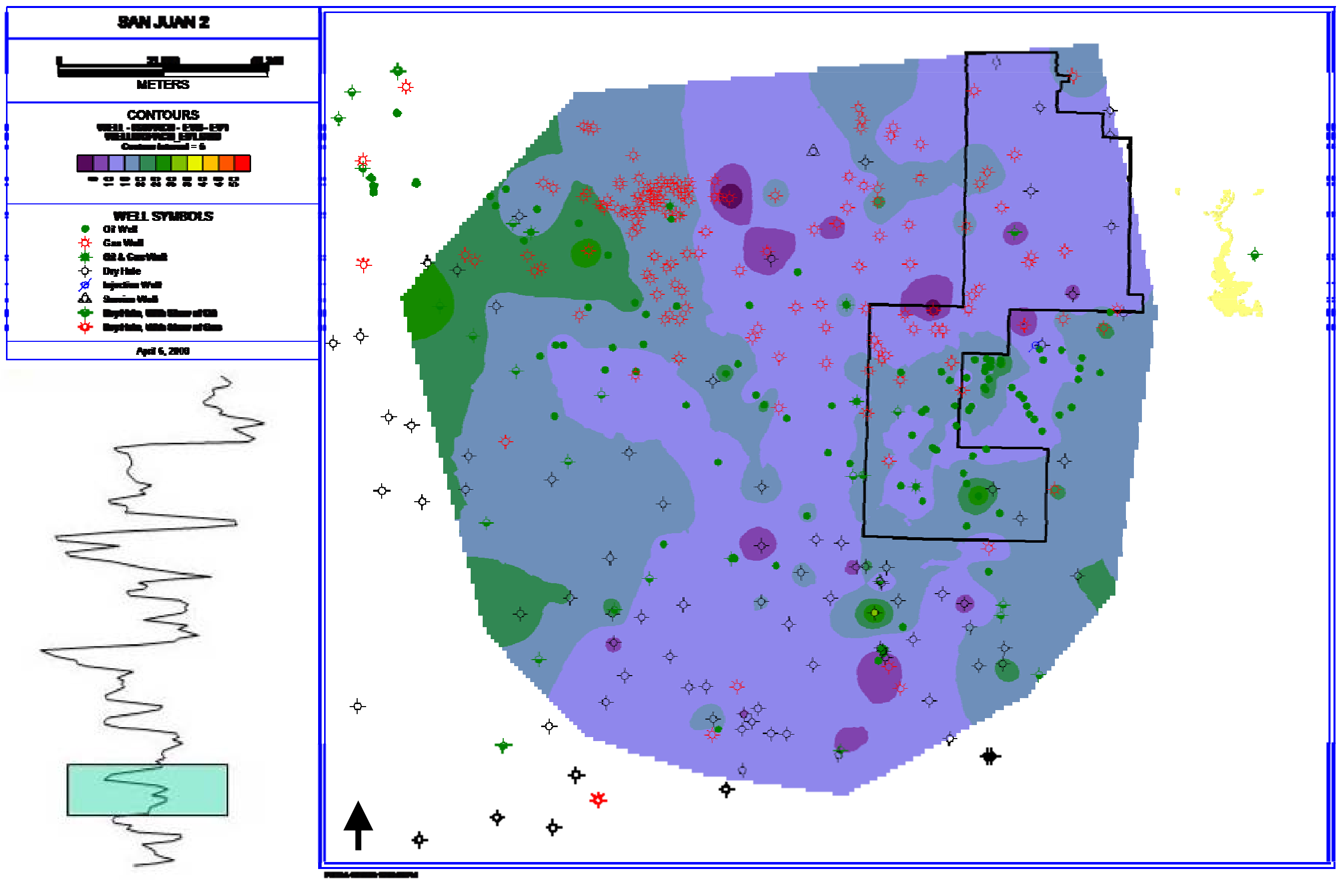


Figure 3.6: Isopach map of the El Vado Sandstone Cycle 1. The interval of thickness is shown in the green shaded log to the lower left of the map. Note the thickening of this interval along the western margin of the map. Color scale from 5 to 50 feet (left to right respectively) with 5 feet increments.

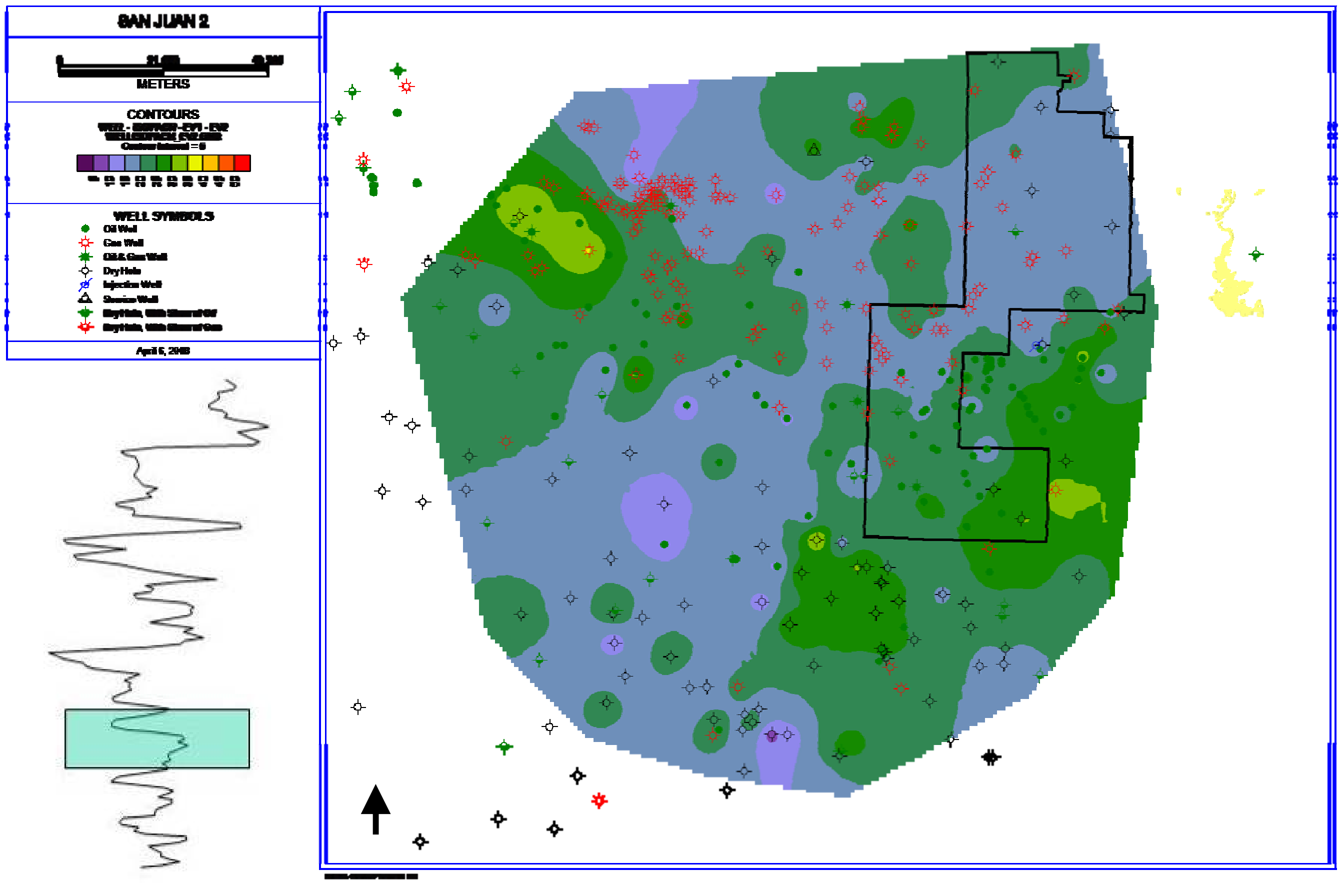


Figure 3.7: Isopach map of the El Vado Sandstone Cycle 2. The interval of thickness is shown in the green shaded log to the lower left of the map. This interval shows similar thickening of the unit to the southeast and western margins of the study area. Color scale from 5 to 50 feet (left to right respectively) with 5 feet increments.

a similarly oriented thinning in the central part of the basin as seen in Cycle 1, however the region of interval thinning has narrowed slightly.

Cycle 3 is the thickest of the Lower El Vado cycles ranging in average thickness of 30 feet (9 m). It does show some minor areas of up to 40 feet (12 m) in thickness. The thickest portion of Cycle 3 trends directly over the top of the underlying thin areas of Cycles 1 and 2, suggesting compensation in deposition on the Lower El Vado shelf (Figure 3.8).

Cycle 4 averages a thickness of 30 to 35 feet (9 to 11 m) with an increased thickness trend of up to 40 feet (12 m) oriented northeast-southwest, that appears to be overlying thinner regions of the underlying Cycle 3 interval (Figure 3.9). There are a few areas of anomalously thick Cycle 4 that might be due to limited data, such as in the northeastern part of the study area.

The fifth and final cycle is approximately 25 to 30 feet thick (8 to 9 m). Once again the thickest area of Cycle 5 appears to overlie an underlying thin area of Cycle 4, suggesting compensated deposition taking place on the El Vado marine shelf (Figure 3.10). The orientation of Cycle 5 thickness trend differs from that of the other cycles, having a more northwest-southeast orientation.

All isopach maps of the El Vado Cycles 3 through 5 show an increase in thickness of the upper cycles to the south and to west of the Jicarilla Apache Reservation. Likewise, these thickness trends appear to be offset from one another, suggesting compensated deposition taking place on the El Vado marine shelf. However, the consistent thickness of the El Vado does not support a case for increased accommodation in specific areas of the shelf, rather it would suggest that the difference in accommodation is purely depositional and compaction. Marine sand sheets vary in their distribution, with subsequent younger cycles preferring locations offset from previous

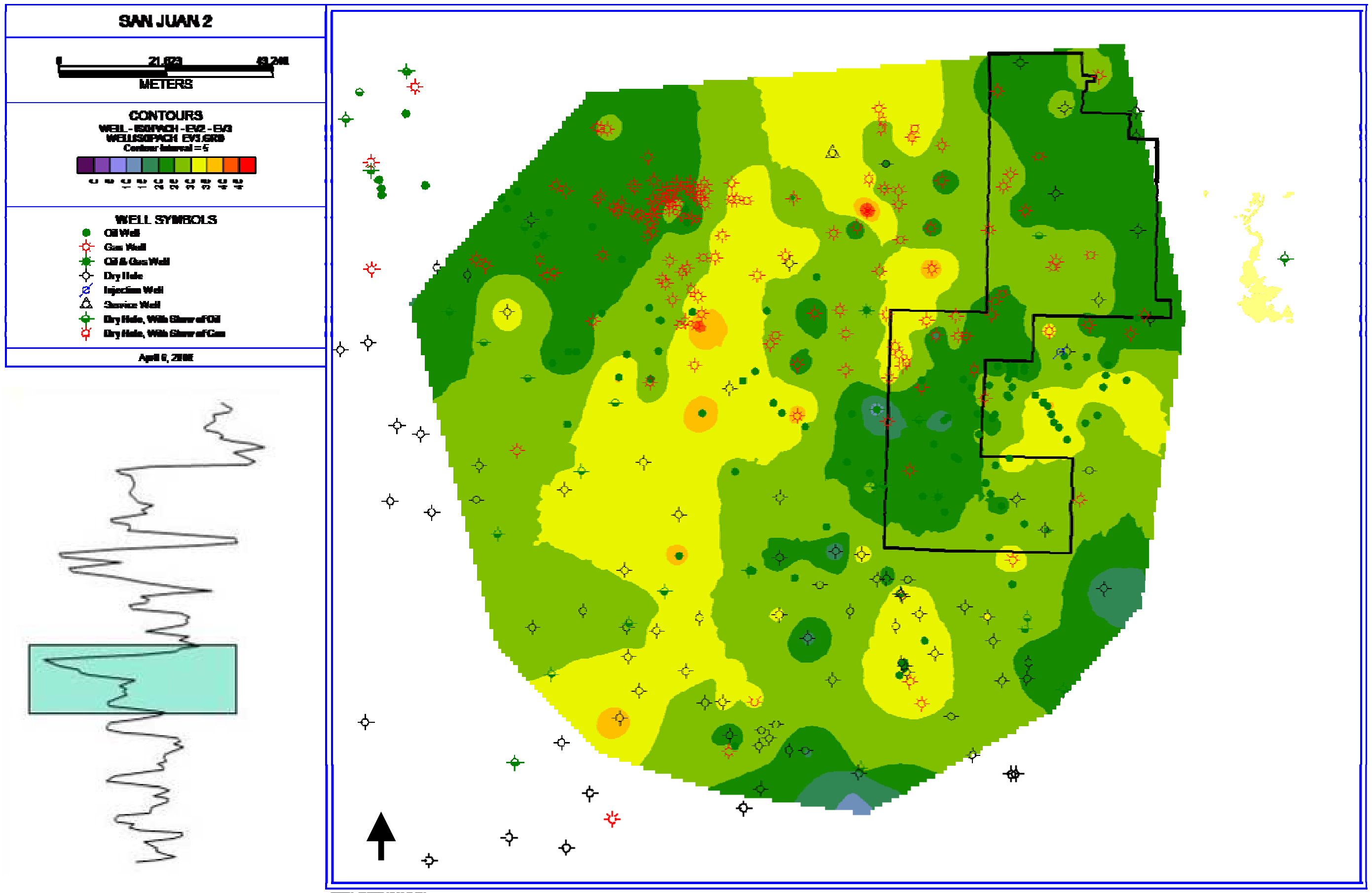


Figure 3.8: Isopach map of the El Vado Sandstone Cycle 3. The interval of thickness is shown in the green shaded log to the lower left of the map. This interval shows the thick areas in yellow oriented northeast-southwest. Color scale from 0 to 45 feet (left to right respectively) with 5 feet increments.

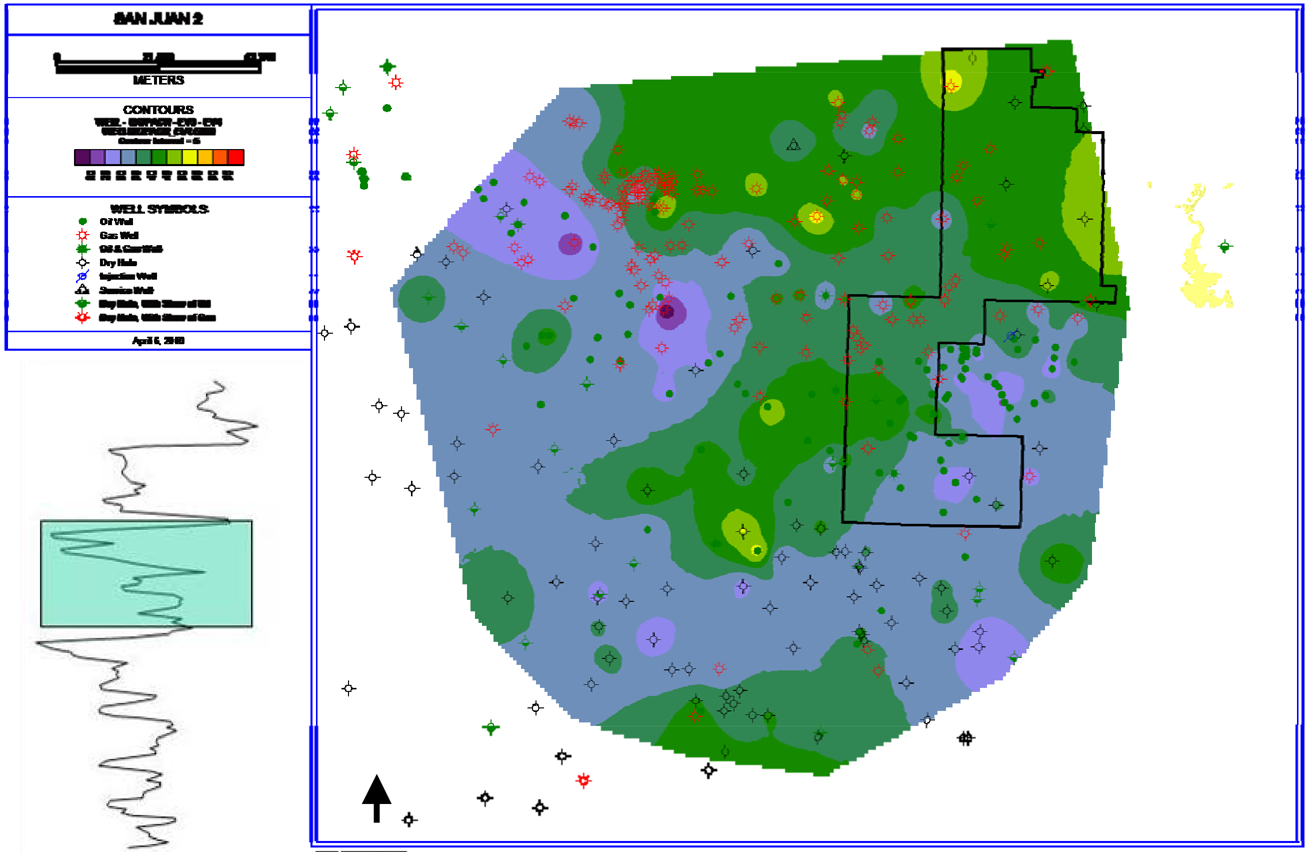


Figure 3.9: Isopach map of the El Vado Sandstone Cycle 4. The interval of thickness is shown in the green shaded log to the lower left of the map. This interval shows thickening oriented in the same direction as the previous cycle, however the deposition is shifted slightly to the east. Color scale from 20 to 65 feet (left to right respectively) with 5 feet increments.

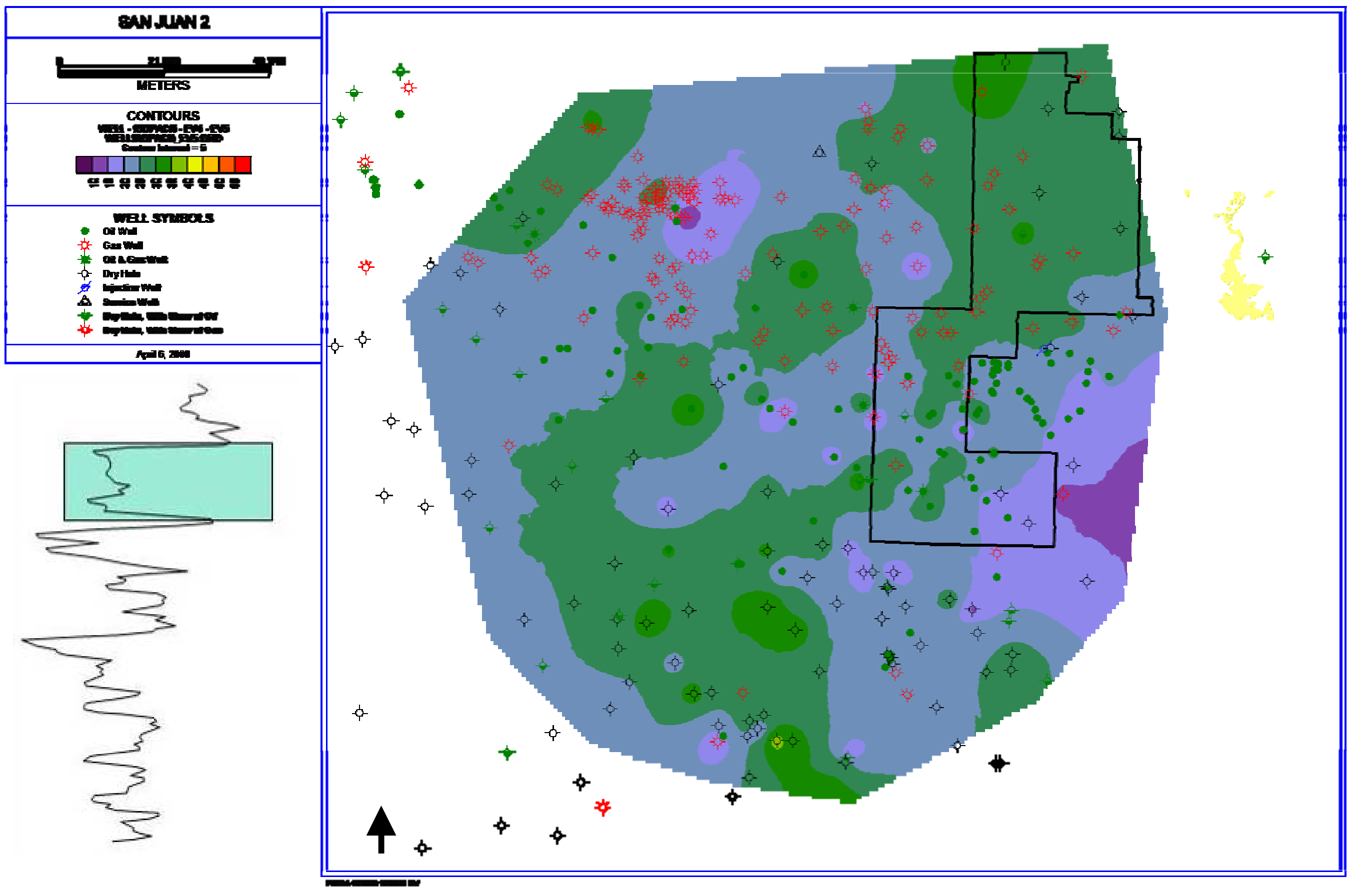


Figure 3.10: Isopach map of the El Vado Sandstone Cycle 5. The interval of thickness is shown in the green shaded log to the lower left of the map. The thick areas in this cycle show deposition in the same orientation, however deposition has slightly shifted around the previous cycle. Color scale from 10 to 55 feet (left to right respectively) with 5 feet increments.

sand thicks. Such behavior can impact exploration and development decisions in that, the area where a cycle is the thickest would be where the previous cycles were thinner (Figure 3.11).

SAND DISTRIBUTION OF THE EL VADO SANDSTONE

Digitized gamma ray well log curves (GR) in 104 wells were normalized to an average baseline and used to generate total and interval net sand and percent sand maps to assess sand distribution patterns in the El Vado Sandstone (using Petra software). It was hypothesized that sand content may vary predicatively relative to the sediment source, being either the ancient shoreline to the south or other possible point sources issuing from the northwest (see Van Wagoner, et al., 1992 for review). To create the net sand map for the entire interval of the El Vado, each individual sand package in each well was picked manually on the GR curve, and the data transferred into a digital database to calculate a net sand map (Figure 3.12). To create interval net sand maps and percent sand maps, a sand-shale cutoff was set in the digitized logs. Since there was little whole core to ground truth to the gamma ray curve expression of sand in this laminated interval it was decided to do a sensitivity test of gamma cutoffs for net sand mapping to decide where to call sand and shale. Cut offs for sand on the GR curve included 80, 105, 120 API based on the type log of the El Vado Sandstone. The cutoffs were chosen from the type log (Figure 3.2) where the sand units were apparent in the GR log.

Net Sand Maps

The net sand map of the entire interval of El Vado Sandstone shows a decrease in the total sand content from the south to north side of the basin (Figure 3.12).

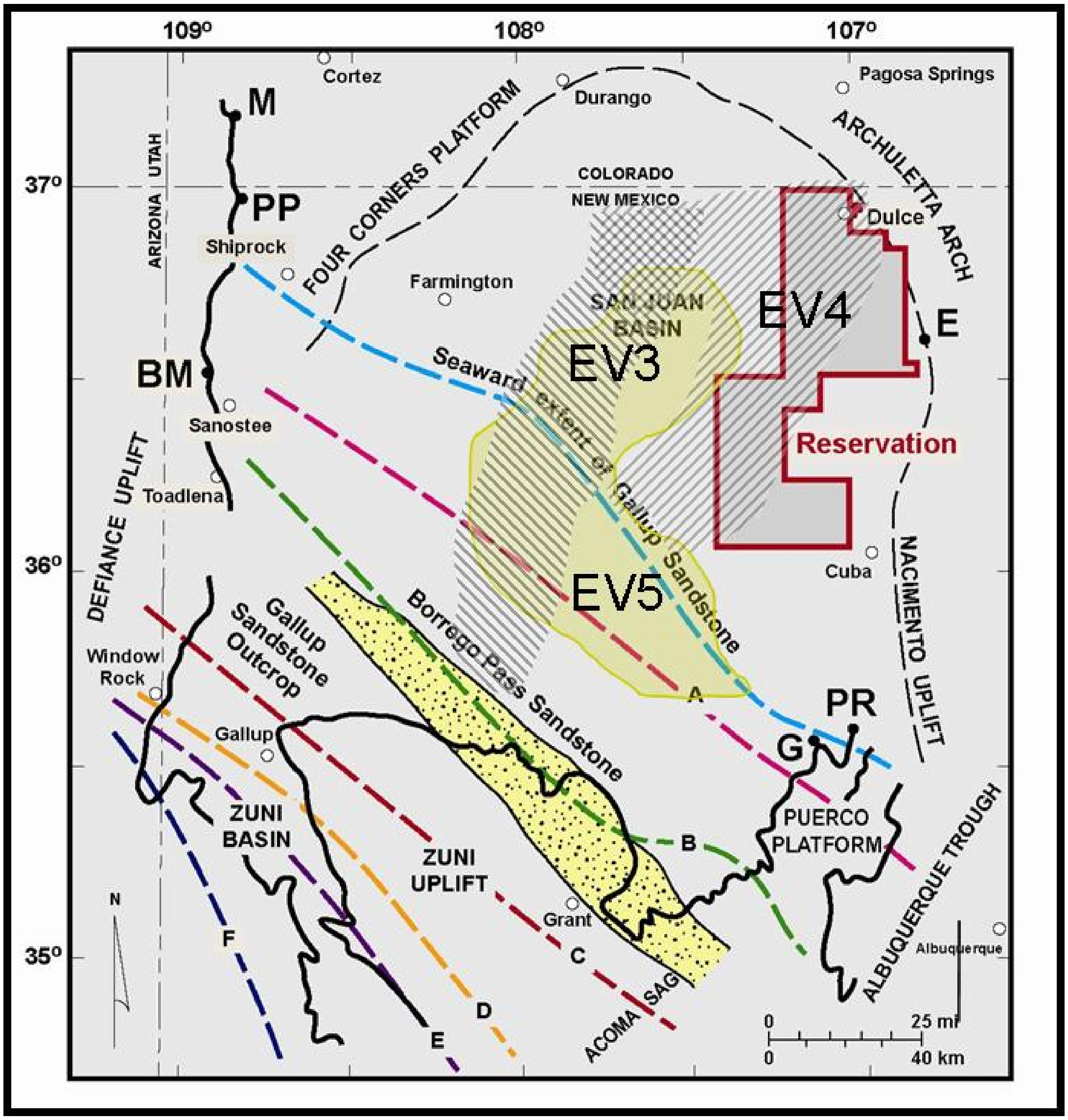


Figure 3.11: Map of the San Juan Basin displaying the thickest areas of deposition in Cycle 3 (EV3), 4 (EV4), and 5 (EV5) of the El Vado Sandstone which would suggest a compensated depositional pattern. Black solid lines reflect the present day outcrop extent. Dashed black lines mark the major structural uplifts bounding the basin. M = Mounds, PP = Pool Plunge, BM = Beautiful Mountain, G = Guadalupe, E = El Vado, PR = Pipeline Road. The extent of the Borrego Pass Sandstone, believed to possibly be equivalent to the Cooper Arroyo Sandstone is shown in yellow. Modified from Ridgley (2001).

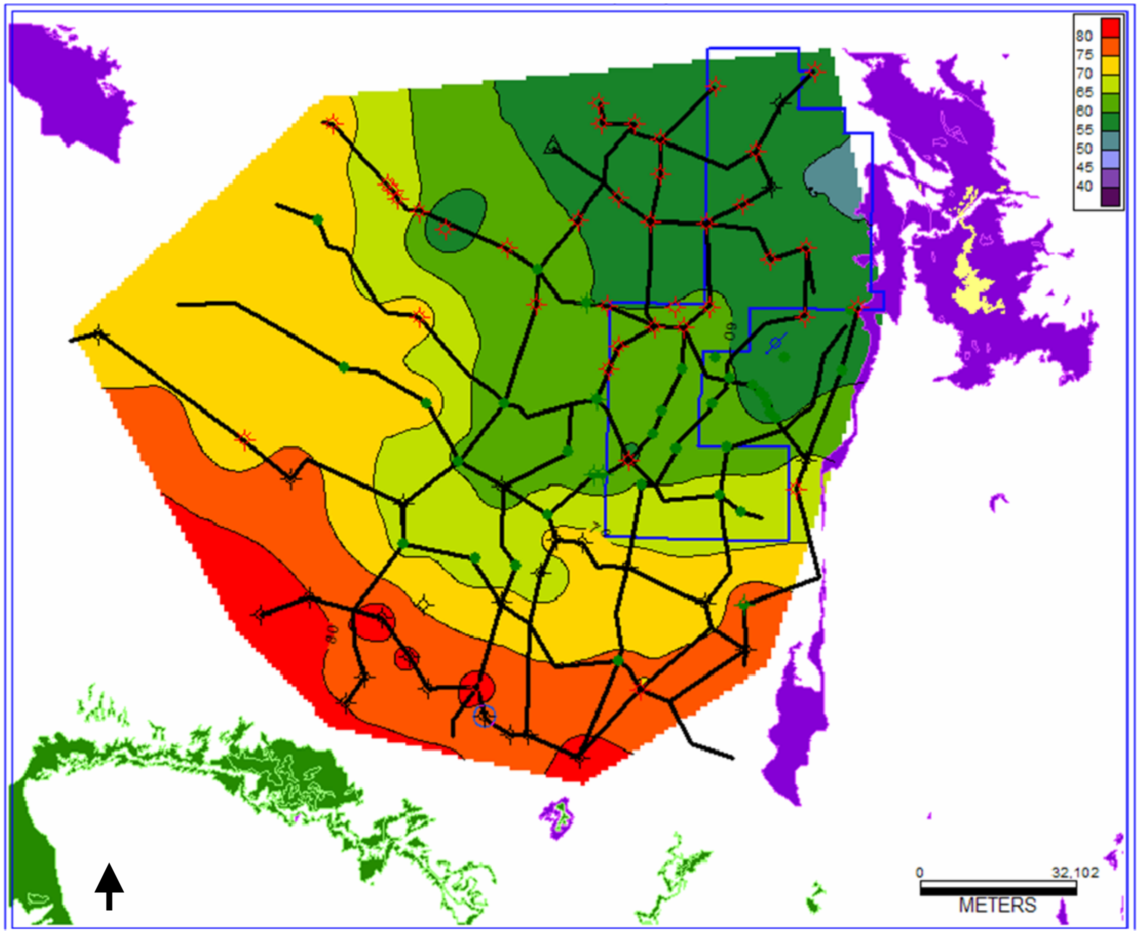


Figure 3.12: Net sand map of the entire El Vado Sandstone interval (increments are in feet). Cross sections are shown as heavy black lines. In general the El Vado sand content is shown decreasing from southwest to northeast across the basin. However, even the lowest values still show the El Vado to contain significant fine-grained sands.

The individual intervals (Cycles 1, 2, 3, 4 and 5) show little obvious trend in net sand changes. Net sand thickness tend to mimic the thickness trends observed in gross interval isopach maps discussed in the previous section. The exception to this trend may be found in the net sand maps generated using a gamma cutoff of 120 API. These maps seem to reflect some south to north change in sand trends.

Net sand maps using a 120 API cutoff for sands show some trends from north to south in Cycles 1 through 5. Cycle 1 and Cycle 2 are very spotty and have several bulls-eyes that make the trend difficult to see. The Cycle 1 net sand map shows a very similar pattern to the isopach map, slightly sandier areas on the east-southeast and west-northwest edges of the basin (Figure 3.13). Cycle 2 shows a slightly different pattern than the isopach map. The net sand map for Cycle 2 shows a less sandy area to the southwest and more sandy to the east and northeast (Figure 3.14).

Cycles 3, 4, and 5 net sand maps are not as spotty as the first two cycles and begin to show sand content trends. The Cycle 3 net sand map shows sandier areas on the east-southeast and west-northwest edges of the basin, similar to Cycle 2 (Figure 3.15). The net sand map shows a general decrease in sand content from southwest to northeast. Cycle 4 shows the opposite trends of Cycle 3. The sandier areas in Cycle 4 are located to the northeast, with a general increase in sand content from southwest to northeast (Figure 3.16). The difference in sand content between Cycle 3 and 4 again shows the patterns of compensated deposition, as discussed in the previous section.

Cycle 5 displays a very different net sand map than any other cycle. In the Cycle 5 net sand map, the orientation of the sand appears to have flipped from southwest-northeast to southeast-northwest (Figure 3.17). The net sand map is similar to the isopach map of Cycle 5 (Figure 3.10). Cycle 5 shows less sandy areas on the east and southwest edges of the basin, with sandy areas located to the northeast and south.

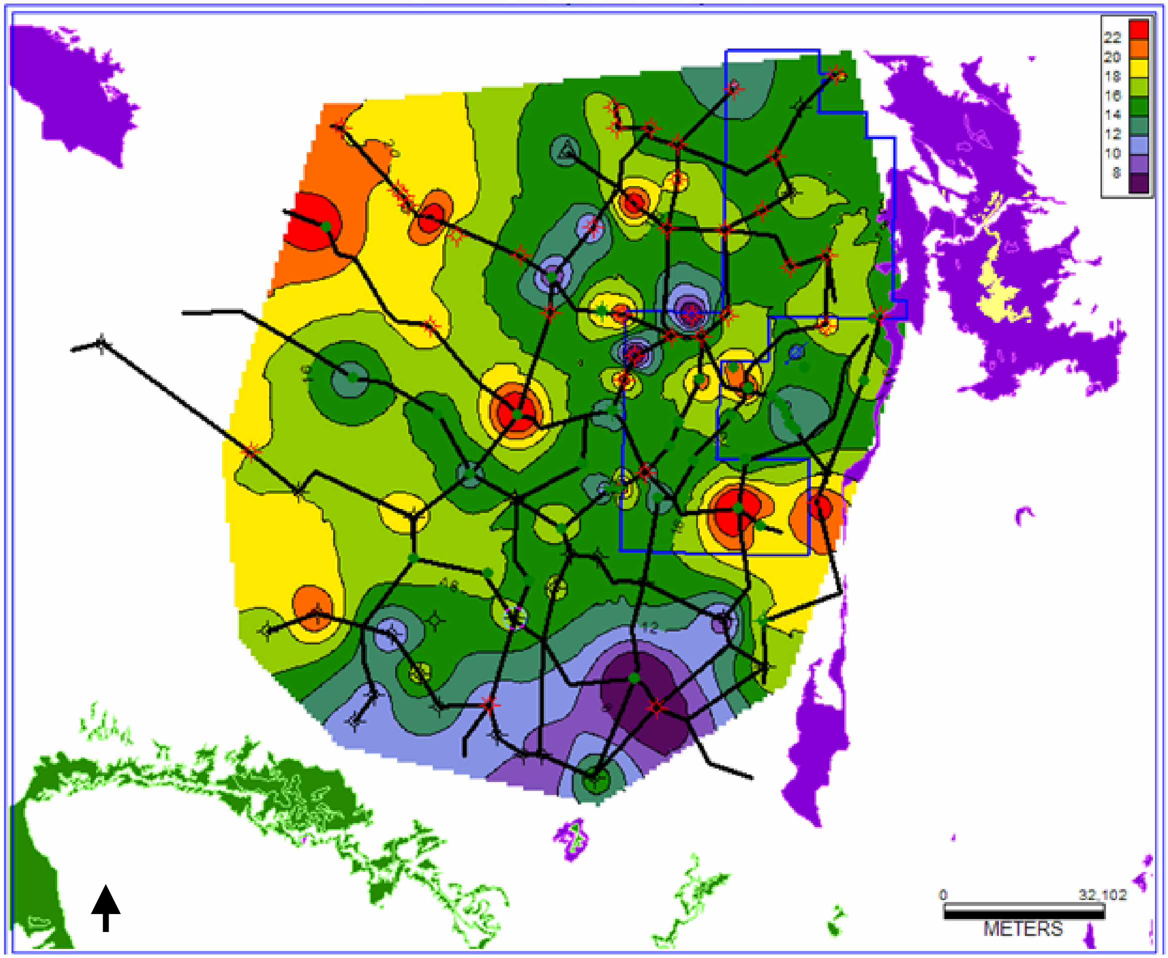


Figure 3.13: Net sand map for Cycle 1, generated using 120 API gamma ray cutoff for sand (increments are in feet).

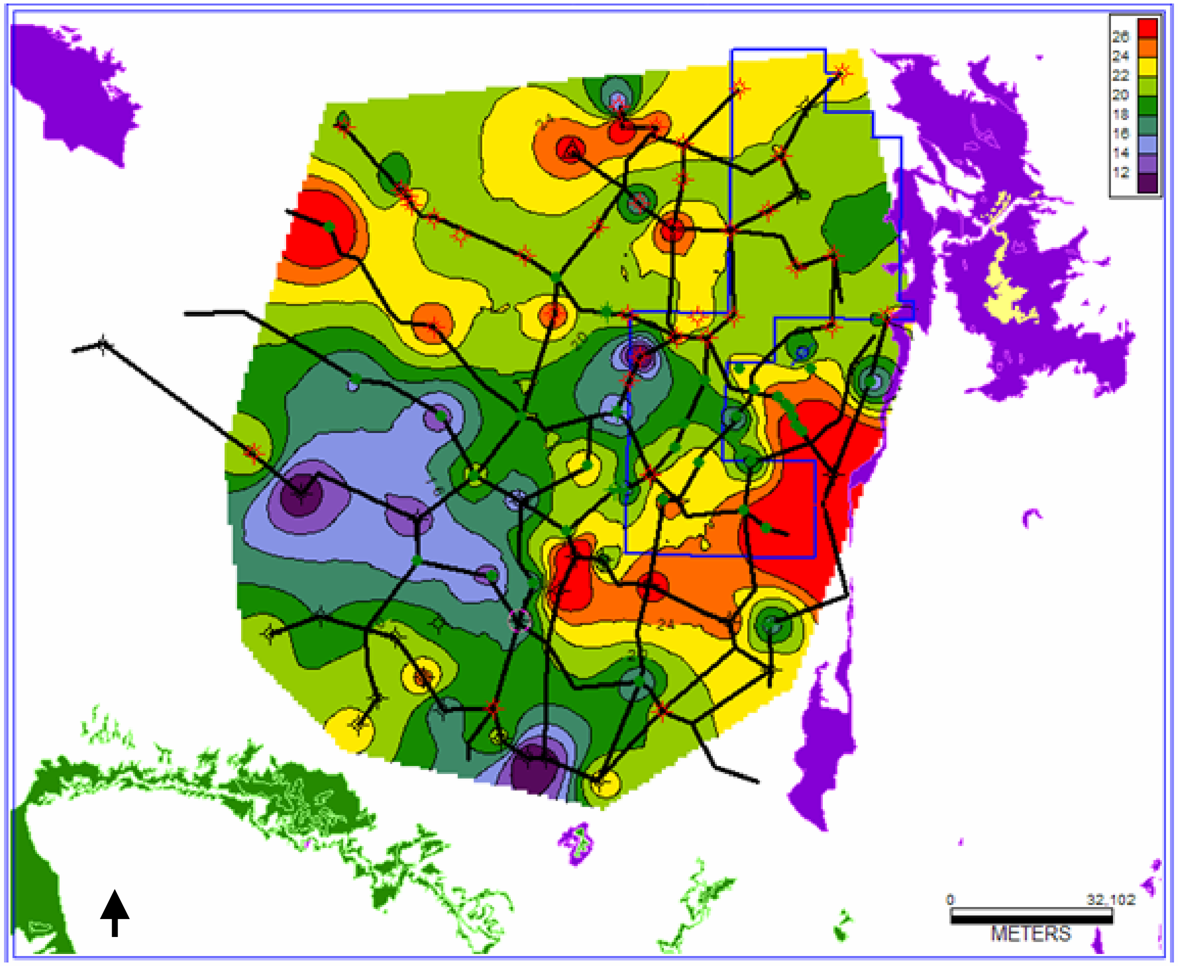


Figure 3.14: Net sand map for Cycle 2, generated using 120 API gamma ray cutoff for sand (increments are in feet).

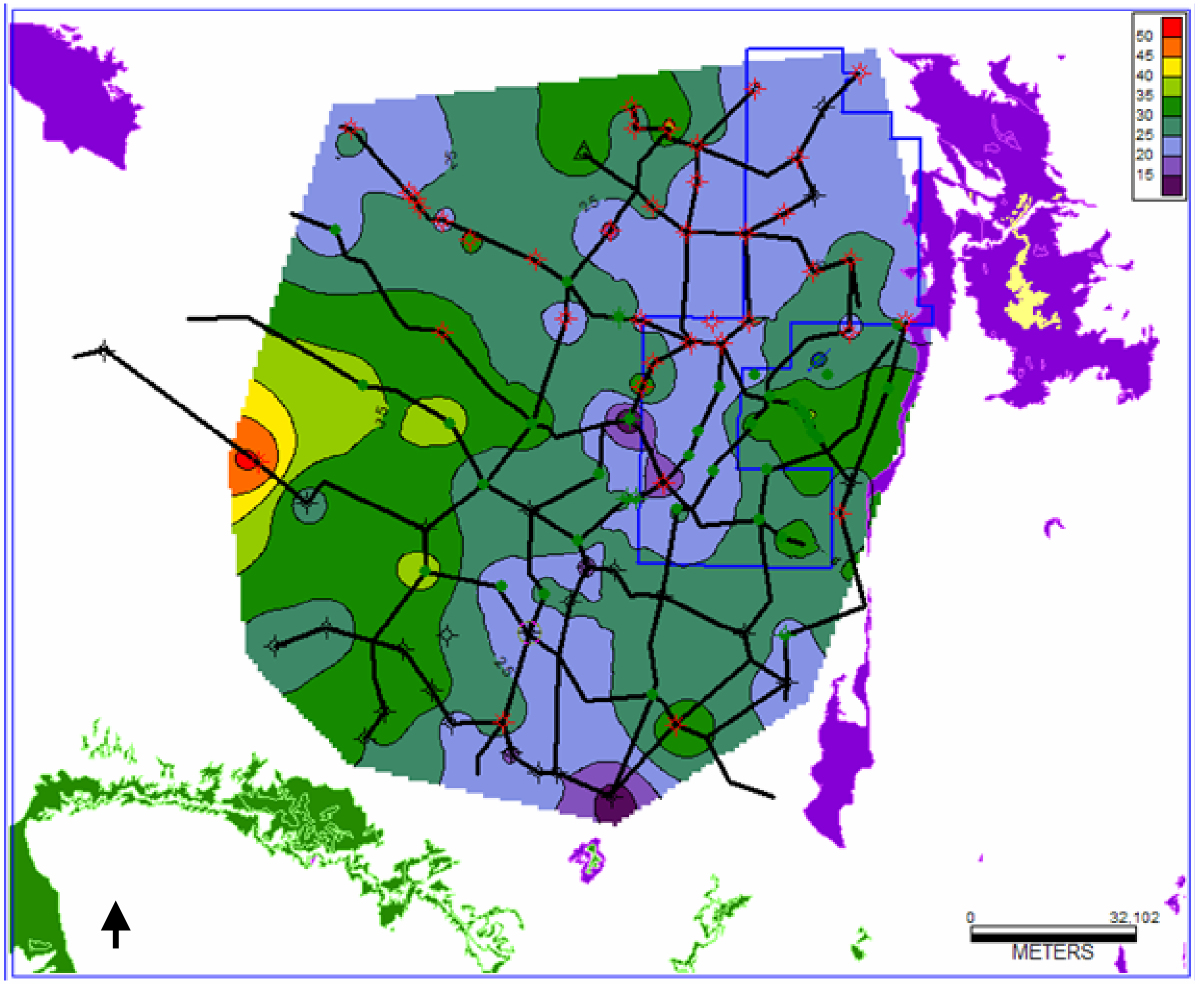


Figure 3.15: Net sand map for Cycle 3, generated using 120 API gamma ray cutoff for sand (increments are in feet).

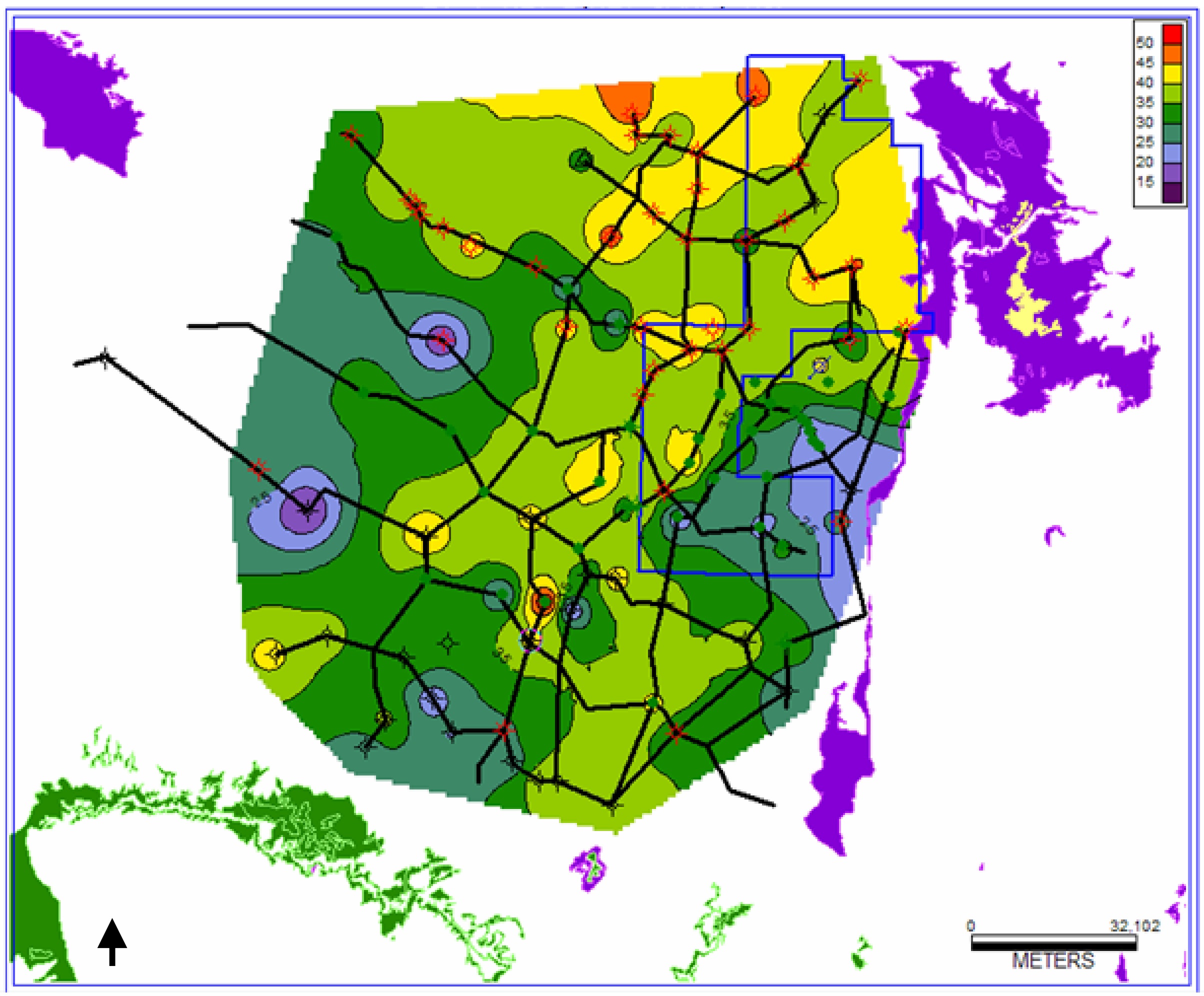


Figure 3.16: Net sand map for Cycle 4, generated using 120 API gamma ray cutoff for sand (increments are in feet).

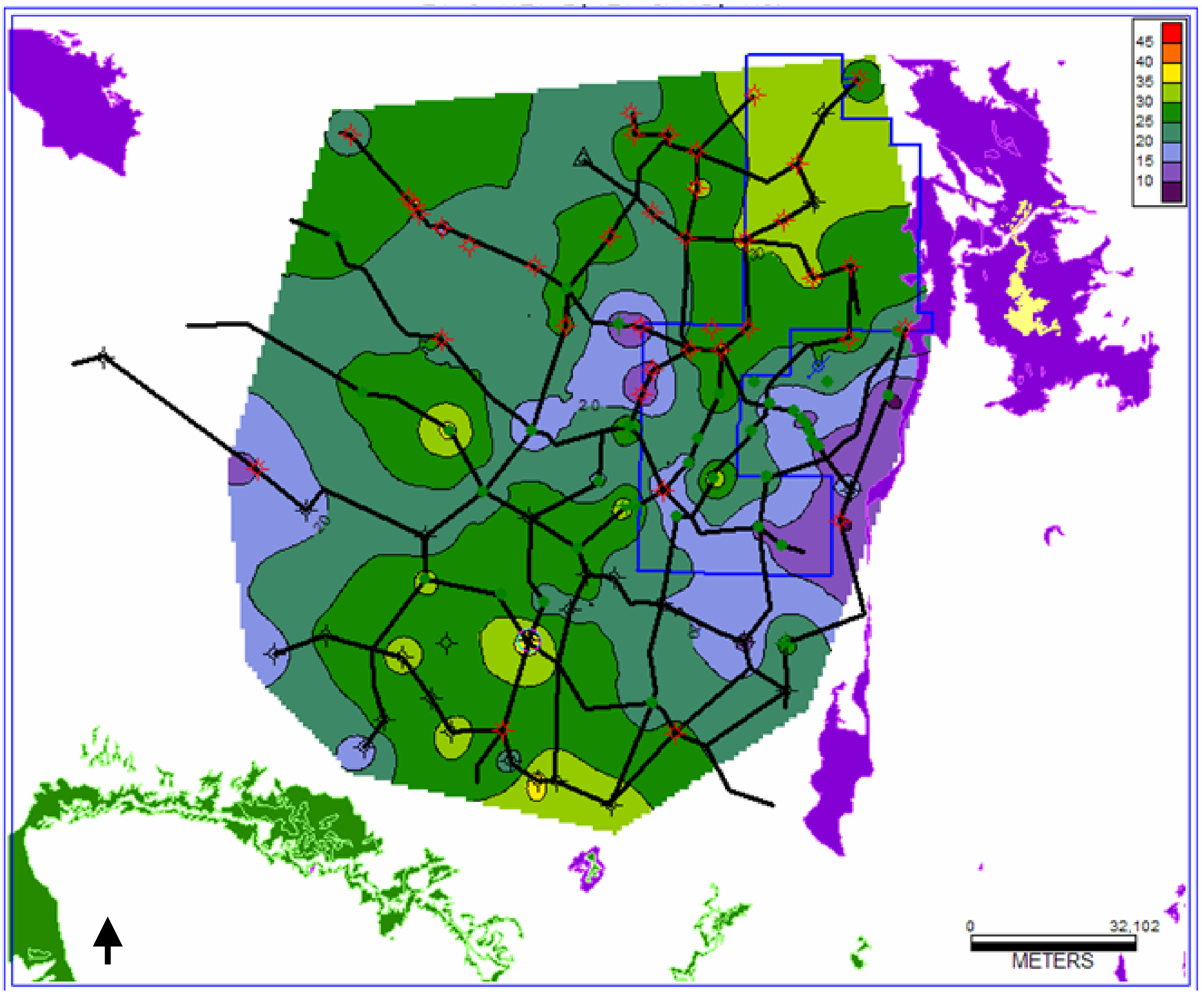


Figure 3.17: Net sand map for Cycle 5, generated using 120 API gamma ray cutoff for sand (increments are in feet).

Net-to-Gross or Percent Sand Maps

Net-to-gross interval maps were generated (using Petra software) by calculating the total sand over an interval using two numbers for sand-shale cutoffs; 100 and 120 API, then dividing those values by the total interval thickness of the specific cycle of interest. These maps were generated to show changes in the amount of sand in an interval relative to the interval thickness.

Sand thickness trends for the El Vado range from 110 to 140 feet (34 to 44 m). Net sand thicknesses tend to show a decrease from south to north across the basin, indicating that although the unit may be maintaining a consistent thickness, more of the unit is composed of shale as you move to the north. Interval net sand thicknesses, as previously noted, tend to mimic the gross isopach thicknesses of the El Vado Sandstone. As discussed in the previous section, these percent thickness trends tend to show some compensated thickness changes oriented south to north. This similarity in pattern between gross interval thickness and net sand suggests that while there may be an overall shaling of the El Vado unit to the north, there is no preferential distribution of sand versus shales on the El Vado shelf in individual intervals, but rather sands and shales are being deposited in equal amounts draping older depositional highs and preferentially filling younger surrounding lows.

Although gross interval thickness and gross interval sand thickness trends tend to show some propensity to orient in a north-south direction, the net-to-gross maps display a trend of decreasing sand content as you go from south-southwest to north-northeast (Figure 3.18). This phenomenon is true regardless of the cut-off value used to generate sand values. See Appendix for all net-to-gross maps.

The overall pattern of the El Vado Sandstone appears to be that of sand decreasing to the northeast, suggesting a possible sand source originating to the southwest. This observation would support Hypothesis 2, that the El Vado Sandstone is a distal shelf facies of the Dalton Shorelines. See the Appendix for all the maps generated.

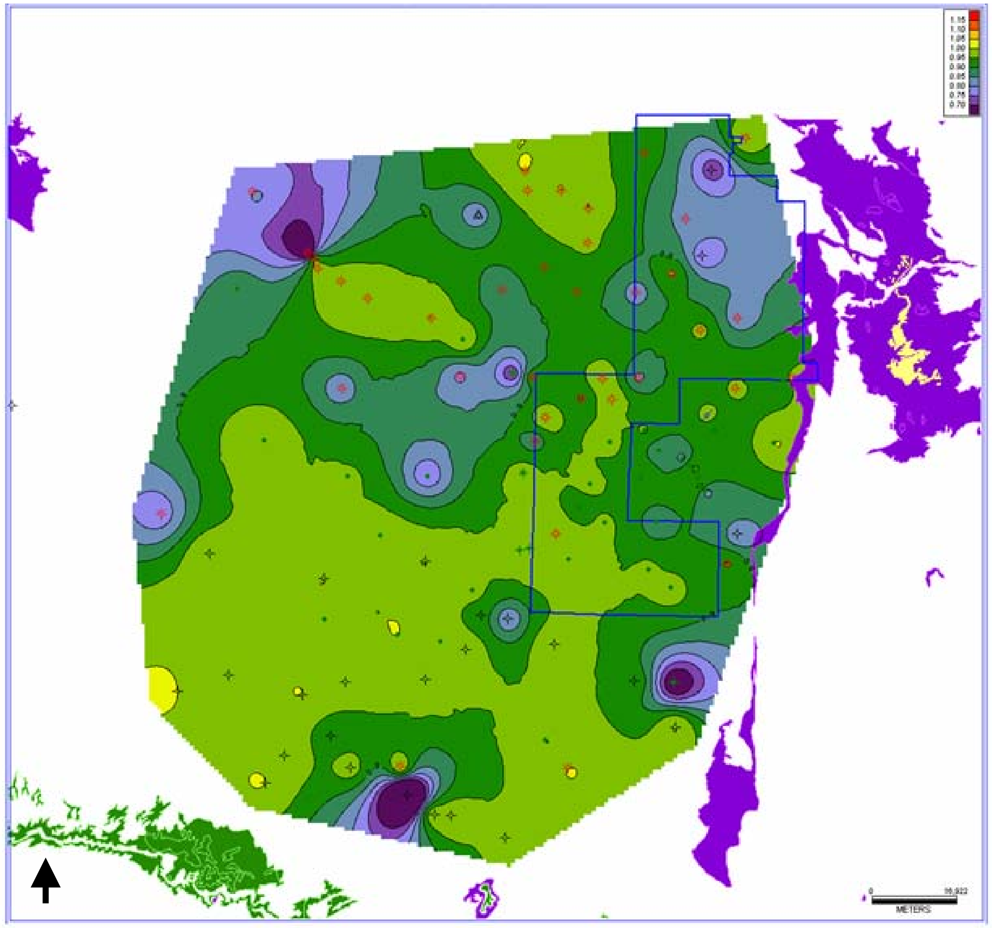


Figure 3.18: Net-to-gross map over the entire interval of the El Vado Sandstone using 120 API as the sand cutoff (value of increments in a ratio of net sand divided by total thickness). Color scale ranges from 1.15 to 0.70 (top to bottom respectively) with increments of 0.05 (N/G ratio).

COMPARISON BETWEEN THE SUBSURFACE AND OUTCROPS

The log character of the El Vado Sandstone appears to strongly resemble the lithology and stacking patterns seen in the El Vado outcrop, with the exception of the strongly transgressive nature of the uppermost cycle. I have been able to document no evidence in outcrop of the top cycle becoming shalier, as is seen in the subsurface logs. To the contrary, each cycle (1 through 5) documented in outcrop appears to coarsen up. It is possible that the shalier Cycle 5 seen in the subsurface has been weathered away leaving behind only the underlying sandier, progradational cycles. However, the El Vado thickness in outcrop is approximately 120 feet (~37 m), similar in thickness to that documented near the northeastern subsurface margin of the basin. In addition, a thorough search for more complete outcrops yielded nothing more than what was documented at El Vado Reservoir. It is possible, that the presence of dolomite or oxidized fecal pellets, as previously discussed, detracts from the sand content of cycle 5 and causes it to appear to become shalier towards its top. However, the dolomite presence would not cause a direct increase in the gamma count.

Chapter 4: Discussion

REGIONAL STRATIGRAPHIC RELATIONSHIPS DURING THE LATE CONIACIAN

The stratigraphic relationship between the El Vado Sandstone and similar aged units of the Tocito Sandstone (to the west), as well as between the El Vado Sandstone and the deposits of the Crevasse Canyon (to the south) and the Dalton Sandstone (to the south) was of importance to fully understand the facies changes that were occurring at any one time across the Mancos shelf. Although no new biostratigraphic data were collected as part of this research, several previous authors have noted biostratigraphic data key to understanding these relationships. Inoceramid and ammonite sequences form the basis for the biostratigraphic analysis (Figure 4.1). Those observations are summarized below as they have significant bearing on the interpretation of the regional stratigraphic relationships mentioned above.

On the southeast side of the basin, the basal part of the Mulatto Tongue separates the Tocito sandstones from the underlying Gallup Sandstone near the village of Guadalupe (Nummedal and Molenaar, 1995). *Cremnoceramus erectus* was reported from the basal Tocito Sandstone and the Gallup Sandstone near Guadalupe, indicating an early Coniacian age (Nummedal and Riley, 1999; Ridgley, 2001). Above the Tocito, *Cremnoceramus crassus* and *C.browni* (both in the *C.deformis* biozone) were recovered from the shale, indicating a late early Coniacian age for this interval (W.A. Cobban, oral commun. from Ridgley, 2001). At the same locality, approximately 100 feet above the Tocito, *Volviceramus involutus* has been recovered (W.A. Cobban, oral commun. from Ridgley, 2001) indicating a middle or late Coniacian age. Slightly higher in the section, both *Volviceramus involutus* and *Magadiceramus stantoni* were found from the sandy shale sequence that is thought to be the El Vado Sandstone (W.A. Cobban, oral commun.

STAGES		AMMONITE SEQUENCE	INOCERAMID SEQUENCE
Santonian	Upper	*Desmoscaphites bassleri*	*Sphenoceramus lundbreckensis*
		Desmoscaphites erdmanni	
		Clioscaphites choteauensis	*Cordiceramus muelleri*
	Middle	*Clioscaphites vermiformis*	*Platyceramus cycloides*
	Lower	*Clioscaphites saxitonianus*	*Magadiceramus subquadratus crenelatus*
Coniacian	Upper	*Scaphites depressus*	*Magadiceramus stantoni*
	Middle	*Scaphites ventricosus*	*Volviceramus involutus* *Volviceramus koeneni*
	Lower	*Forresteria alluaudi*	*Cremnoceramus deformis* *Cremnoceramus erectus* *Cremnoceramus waltersdorfensis*
Turonian	Upper	*Forresteria peruana*	*Mytiloides scupini*
		Prionocyclus germari	
		Prionocyclus quadratus	*Mytiloides incertus*
		Scaphites nigricollensis	
		Scaphites whitfieldi	*Inoceramus dakotensis* *Inoceramus perplexus*
	Middle	*Scaphites ferronensis*	
		Scaphites warreni	*Inoceramus dimidius*
		Prionocyclus macombi	
		Prionocyclus hyatti	*Inoceramus howelli*
		Collignoniceras praecox	
		Collignoniceras woollgari	*Mytiloides hercynicus* *Mytiloides subhercynicus*

Figure 4.1: Biostratigraphy in the study area, focusing on the Coniacian. Chart was taken from Ridgley 2001, which was provided by W.A. Cobban.

from Ridgley, 2001). *Magadiceramus stantoni* indicates a late Coniacian age for these strata (Ridgley, 2001).

To the northeast, near the El Vado Reservoir and below the El Vado type section, lies the Cooper Arroyo. Although the Cooper Arroyo Sandstone has been described by other authors (Ridgley, 2001) as "…a Tocito-like sandstone…", it was noted in this research that the Tocito on the eastern side of the basin is composed of a pervasive amount of hummocky cross-stratified, fine-grained sands (Figure 4.2). This facies is very different than the Cooper Arroyo in outcrop (see previous discussion). However, the Cooper Arroyo does contain a *Cremnoceromus deformis* fauna (W.A. Cobban, oral commun. from Ridgley, 2001), which is the same zone as the lowermost Tocito sandstones at the Guadalupe outcrop (Ridgley, 2001). Above the Cooper Arroyo, at the El Vado type section, there is about 150 to 180 feet of shale (Landis and Dane, 1967) that separates it from the El Vado Sandstone. *Volviceramus involutus* was found throughout this shale and also in the El Vado Sandstone (King, 1974) indicating middle through upper Coniacian age for this section. The position of *V. involutus* relative to the Cooper Arroyo Sandstone is similar to that found at the Guadalupe outcrop (Ridgley, 2001). At El Vado Reservoir, approximately 45 feet above the first appearance of *Volviceramus involutus*, I. sp. (radial ribs) were recovered and these inoceramids are now thought to represent *Magadiceramus subquadrants crenelatus* (Ridgley, 2001). These inoceramids were found in the remainder of the El Vado Sandstone. *Magadiceramus subquadrants crenelatus*, found in the El Vado type section is also found in the first major regressive sandstone of the Dalton Sandstone and the shale immediately below it (B and C intervals of the Dalton) and indicates late Coniacian age (Ridgley, 2001).

Figure 4.2: Photo from the Tocito Sandstone located west of Cabezon Peak in the south of the San Juan Basin. Note the hummocky cross-strata.

Thus, the El Vado Sandstone at El Vado Reservoir and the El Vado at the Guadalupe outcrop are both late Coniacian in age (Figure 4.3).

The oldest Tocito Sandstone, Tocito Sequence 1, bounded at the base by the oldest sequence boundary of Jennette and Jones (1995), on the west side of the San Juan Basin is within the range of *Cremnoceramus deformis* of late early Coniacian age (Ridgley, 2001). *Magadiceramus stantoni* was reported from the Tocito Sandstone, Tocito Sequence 4 that rests on the youngest sequence boundary of Jennette and Jones (1995) in the Beautiful Mountain area (Nummedal and Riley, 1999; Ridgley, 2001) indicating late Coniacian age. This biostratigraphic data supports an interpretation of the El Vado Sandstone Cycle 4 and 5 (Upper El Vado) of the type section, near El Vado Reservoir, being age equivalent to the Tocito Sequence 3 and 4 on the west side of the San Juan Basin, a late Coniacian deposit.

Jennette and Jones (1995) defined four units of the Tocito which they interpreted as being deposited in a series of estuarine valley that were structurally controlled and oriented northwest to southeast. Nummedal and Riley (1999) alternatively suggested that the sequences of the Tocito on the western side of the basin were shelf sands whose orientations paralleled the paleo Gallup coastline and whose thicknesses were anomalously influenced by offshore structures during the Coniacian. Snedden (pers. comm. 2007) suggested on the basis of lithologic and paleontologic differences that the lower two units of the Tocito are valley fill (regressive) and the upper two units may be estuarine to open shelf deposits (transgressive). Similar to the Tocito, the El Vado Sandstone appears to be composed of four to five cycles, divided into two major cycles by a regional marine shale. Based on the limited regional biostratigraphic markers and stacking patterns (progradational versus retrogradational), as well as the overall depositional setting of the Coniacian units within the San Juan Basin, I believe

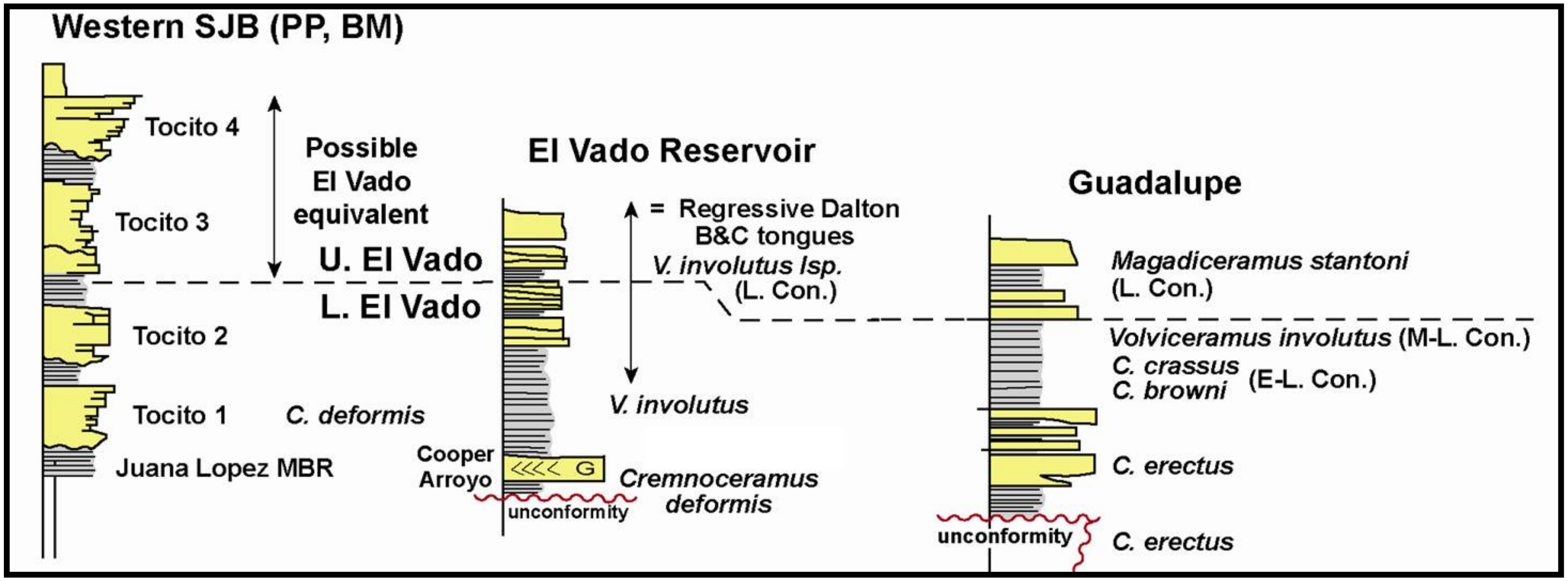


Figure 4.3: Regional biostratigraphic relationships across the San Juan Basin. The western outcrops are called Beautiful Mountain and Plunge Pool. The El Vado Reservoir is located in the northeast and the Guadalupe outcrop is located in the southeast. The outcrops are not drawn to scale.

that the Regional Shale likely separates the El Vado into a regressive Lower El Vado (cycles 1, 2, and 3) correlative to the west with the Tocito units 1 and 2 (regressive), and a transgressive Upper El Vado (cycles 4 and 5) correlative to the west with the Tocito units 3 and 4 (transgressive).

DEPOSITIONAL ENVIRONMENTS OF THE EL VADO SANDSTONE

The El Vado Sandstone Member of the Mancos Shale was examined in two primary localities in outcrop to document the facies and petrography, as well as mapped in the subsurface to assess its distribution patterns towards interpreting the environment of deposition. The outcrops of the El Vado Sandstone to the south show an abundance of hummocky cross-stratification (HCS) in very fine to fine-grained sandstones, which is a widely accepted indication of storm deposits in shoreface and shallow marine settings (Walker and Plint, 1992). A typical wave-dominated shoreface succession begins with outer and mid-shelf deposits consisting of mudstones and interbedded sandy siltstones and then transitions into lower shoreface deposits consisting of sandstones interbedded with siltstones and hummocky cross-stratification (Walker and Plint, 1992). This is the same succession seen in the outcrop northwest of Cabezon peak (southern outcrops). This evidence suggests deposition in a marine shelf setting shallowing up to a lower shoreface (Walker and Plint, 1992). Swift and Parsons (1999) listed hummocky cross-stratification as one criteria of a shoreface deposit in their facies of the Shannon Sandstone. In addition to HCS the presence of some trace fossils may also support a shoreface deposit. Thalassinoides was found in the upper section of the outcrop with HCS beds. Pemberton et al. (1992) place Thalassinoides in the sandy shore Cruziana ichnofacies. In contrast, the El Vado to the north is a continuous sheet-like deposit of interlaminated silty shales and thin sand beds. The uppermost beds contain abundant oyster shell hash. These northern units are interpreted as being deposited in a more distal lower shoreface to shelfal setting, further from the sourcing shoreline. Deposition of similar shelf sands in the same area but younger in the basin's history have been interpreted by Palmer and Alan (1984) as being strongly influenced by strong coastal currents interacting with paleodeltaic headlands to result in inconsistent sand deposition on the shelf.

Although admittedly weak an argument can be made that the El Vado Sandstone Member of the Mancos Shale (Landis and Dane, 1967) is a distal shelf facies of the B and C shorelines of the Dalton Sandstone, rather than begin fed directly from the Tocito valleys to the west. The supporting evidence includes that:

(1) The El Vado Sandstone shows an overall pattern of facies deepening from south to north rather than from east to west, as would be expected if it were sourced from the west.
(2) Well log correlations show the El Vado extending southward to the southern outcrop with sand percentages varying in areas that parallel the southern shoreline trend, rather than thickening to the west as would be suggested by a Tocito valley source.
(3) The lower El Vado shows no grain size change as would be expected with a direct link to a lowstand Lower Tocito valley, as interpreted by both Jennette and Jones (1995) and Snedden (pers. comm., 2007). The lower cycles of the Tocito in the western San Juan Basin, were observed by the author to show a very coarse grain size, very dissimilar to the lower El Vado.

HYDROCARBON PROSPECTIVITY

Tight gas sands such as the El Vado have been proven to contain great potential for heretofore unrealized gas and oil reserves (Ridgley, 2001). Although production appears to be co-mingled in the area wells making it difficult to assess direct production from the El Vado, most all wells that showed El Vado perforation were successful. This suggests that those dry holes where the El Vado was not perforated may warrant revisiting for low permeability pay in the El Vado.

Isopach maps show that increased exploration success may be had by expanding drilling to the south (up dip in the migration pathway) and west, where continuous El Vado sands intersect structures associated with pre-or-early Laramide structuring. Compensated deposition of sand bodies on the El Vado shelf provides the potential for stacked pay in some areas of the basin (Figure 4.4). From Ridgley's (2001) report, she conclude that the central and southern part of the Reservation, large areas, currently not productive or not tested, have the potential to contain oil in the El Vado simply based on the trend of facies and structure.

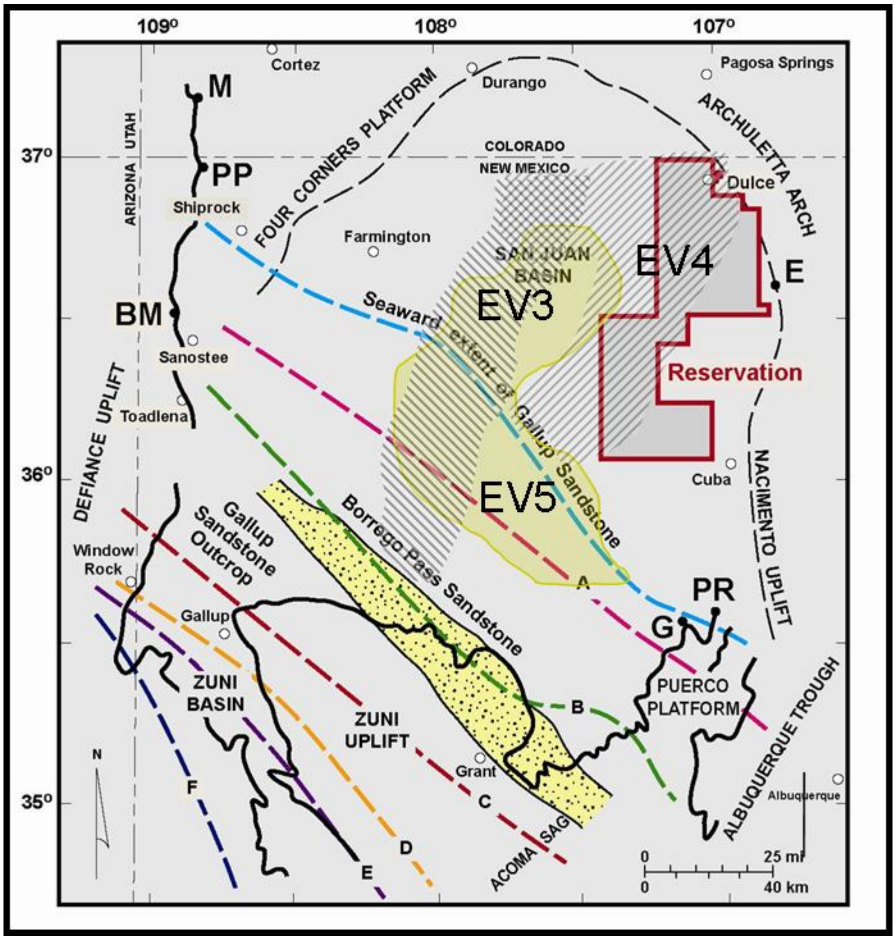


Figure 4.4: Possible exploration potential lies to the south and to the west of the Jicarilla Apache Reservation. This map shows again the accumulation of the thick areas of cycles 3 (EV3), 4 (EV4), and 5 (EV5). Black solid lines reflect the present day outcrop extent. Dashed black lines mark the major structural uplifts bounding the basin. M = Mounds, PP = Pool Plunge, BM = Beautiful Mountain, G = Guadalupe, E = El Vado, PR = Pipeline Road. The extent of the Borrego Pass Sandstone, believed to possibly be equivalent to the Cooper Arroyo Sandstone is shown in yellow. Modified from Ridgley (2001).

Chapter 5: Conclusions

The El Vado Sandstone Member of the Mancos Shale (Landis and Dane, 1967) is part of a transgressive-regressive wedge of rock that overlies the Gallup unconformity in the San Juan Basin, located in northwestern New Mexico. Like many shelf sand deposits the El Vado Sandstone is a highly productive hydrocarbon reservoir interval; however its nature and origin are poorly understood. The objective of this thesis was to answer key questions that could help to understand the sandstone and improve production in the San Juan Basin.

The El Vado Sandstone consists of five individual progradational-retrogradational cycles, that stack to form a lower El Vado (consisting of cycles 1, 2, and 3) and an upper El Vado (consisting of cycles 4 and 5) separated by an intervening Regional Shale. It was deposited as a lower shoreface to shelf facies in the south (near the Village of Guadalupe) deepening to distal shelf facies to the north (near El Vado Reservoir). The El Vado Sandstone is interpreted to be of some time equivalence to the Tocito Sandstone along the western side of the San Juan Basin, but is most closely sourced by the shorelines of the Dalton Sandstone, located to the south. In the subsurface, the El Vado maintains a fairly consistent thickness (fluctuating 5-10 feet) throughout the San Juan Basin. However, individual cycles show some variability in thickness that is attributed to compensated deposition occurring on the El Vado shelf. Likewise, sand thickness shows some variability with sand percentages in some intervals decreasing to the north, northeast, and some intervals showing a distinct zone of decreased sand values trending northwest to southeast across the basin. All of these sand percentage trends parallel a southern shoreline and suggest strong influence of longshore currents influencing sand distribution in the El Vado Sandstone.

Additional research in the El Vado Sandstone and associated units can only improve the observations made in this study. Additional biostratigraphic data from the intervals above the Gallup will improve our understanding of the stratigraphic relationships in the basin and enable improved models of how sand facies transition across such interior basins. Reexamination of the Tocito in the eastern side of the basin and more detailed facies work on the Tocito in the western side of the basin will aid in understanding the facies distribution of the Tocito interval. New outcrops of the Tocito which have not been studied before were identified in the southern part of the eastern SJB which can lead to a better regional understanding of this important hydrocarbon system.

Appendix

Section of El Vado Sandstone Member
at the type section

	Ft	In.
UPPER SHALE UNIT		
Shale, medium gray, soft		
El Vado Sandstone Member		
Sandstone, very fine-grained, and siltstone, calcareous, yellowish gray on fresh fracture and weathered surface, some beds harder and more calcareous, beds fraction of an inch to several inches thick, upper few feet weather back from ledge face. Some ripple bedding	17	0
Shale, medium gray, silty, makes notch	1	0
Sandstone, very fine-grained, and siltstone, forms a ledge with the two overlying units	5	0
Shale, silty, medium gray, forms persistent slope, transitional into overlying unit	27	0
Siltstone, and very fine-grained sandstone, calcareous, thin-bedded, brownish gray, weathers yellowish gray, minutely micaceous, with oyster fragments. Cross-bedding within the unit results in increase of thickness of subunits from 1 to 2 feet along the outcrop. Whole unit makes a ledge that appears to maintain a uniform thickness	10	0
Shale, gray and silty shale, soft, makes a persistent notch in cliff	9	0
Siltstone and very fine-grained sandstone, thin-bedded, calcareous, brownish gray, weathers yellowish gray, minutely micaceous and with many shell fragments	11	0
Shale, medium gray, interbedded with silty shale and siltstone, makes slope or small notch in cliff	6	3
Siltstone, shaly and silty shale, yellowish gray, weathers grayish orange, in beds a small fraction of an inch to one inch thick, base of unit transitional with underlying beds but fairly sharp, unit has more and harder siltstone beds upward	13	7
Total El Vado Sandstone Member	99	10

In exposures in the southeastern part of the Tierra Amarilla quadrangle, north of Rio Nutrias, El Vado Sandstone Member contains more plates of *Inoceramus platinus* encrusted with *Ostrea congesta*, comminuted fish remains, ripple marks, and trail and other marks than are recorded in the type section. This reflects some slight local variation in the lithology of the member, but no significant differences occur and the thickness is nearly the same.

Figure A.1: Original description of the El Vado Sandstone from Landis and Dane (1967).

Section of Cooper Arroyo Sandstone Member
at the type section

Middle shale unit	Ft	In.
Upper part		
Shale, dark gray, silty, calcareous, with float of *Inoceramus platinus,* which occurs in place in beds not many feet higher		
Cooper Arroyo Sandstone Member		
Sandstone, coarse-grained, with a few very coarse grains, in beds ½ in. to 4 in. thick abundantly glauconitic. In cross sections, beds have wavy upper and lower surfaces as though ripple-bedded with a wave length of 3 to 8 in., but ripple mark not evident on irregular, upper weathered surface. Upper surface marked by smooth-surfaced tubular borings. Contains small, black, dense, siliceous pebbles up to ½ in. in diameter. The thickest coarse bed is cross-bedded at angles of as much as 25 degrees	1	10
Sandstone, medium-grained, abundantly glauconitic, in irregular beds ½ in. to 1½ in. thick, with a very slightly irregular undersurface	0	10½
	2	8½
Lower part		
Shale, silty, olive-gray, micaceous, weathers medium gray, contains minute carbonaceous plant fragments		

At a few localities, the Cooper Arroyo Sandstone Member has a small fauna, identified by W. A. Cobban, that includes *Inoceramus erectus,* which is an index species of early, but not earliest, Niobrara age, *Placenticeras* sp., *Ostrea congesta,* and fish teeth.

El Vado Sandstone Member (Kme) (90 to 100 ft thick)

El Vado Sandstone Member of the Mancos Shale crops out extensively in the eastern part of the quadrangle and is well exposed in prominent westward-facing escarpments both north and south of Rio Nutrias. It is here named from outcrops west of El Vado Reservoir in the Boulder Lake quadrangle, where it makes a conspicuous low escarpment below high cliffs of the Mesaverde Group. The type section was measured in the Boulder Lake quadrangle below the 7388-foot altitude point located 2.4 miles east and 1 mile north of the southwest corner of the Tierra Amarilla Grant and about 2 miles southwest of the emergency overflow outlet for El Vado Reservoir shown on the Tierra Amarilla quadrangle map.

Figure A.2: Original description of the Cooper Arroyo Sandstone from Landis and Dane (1967).

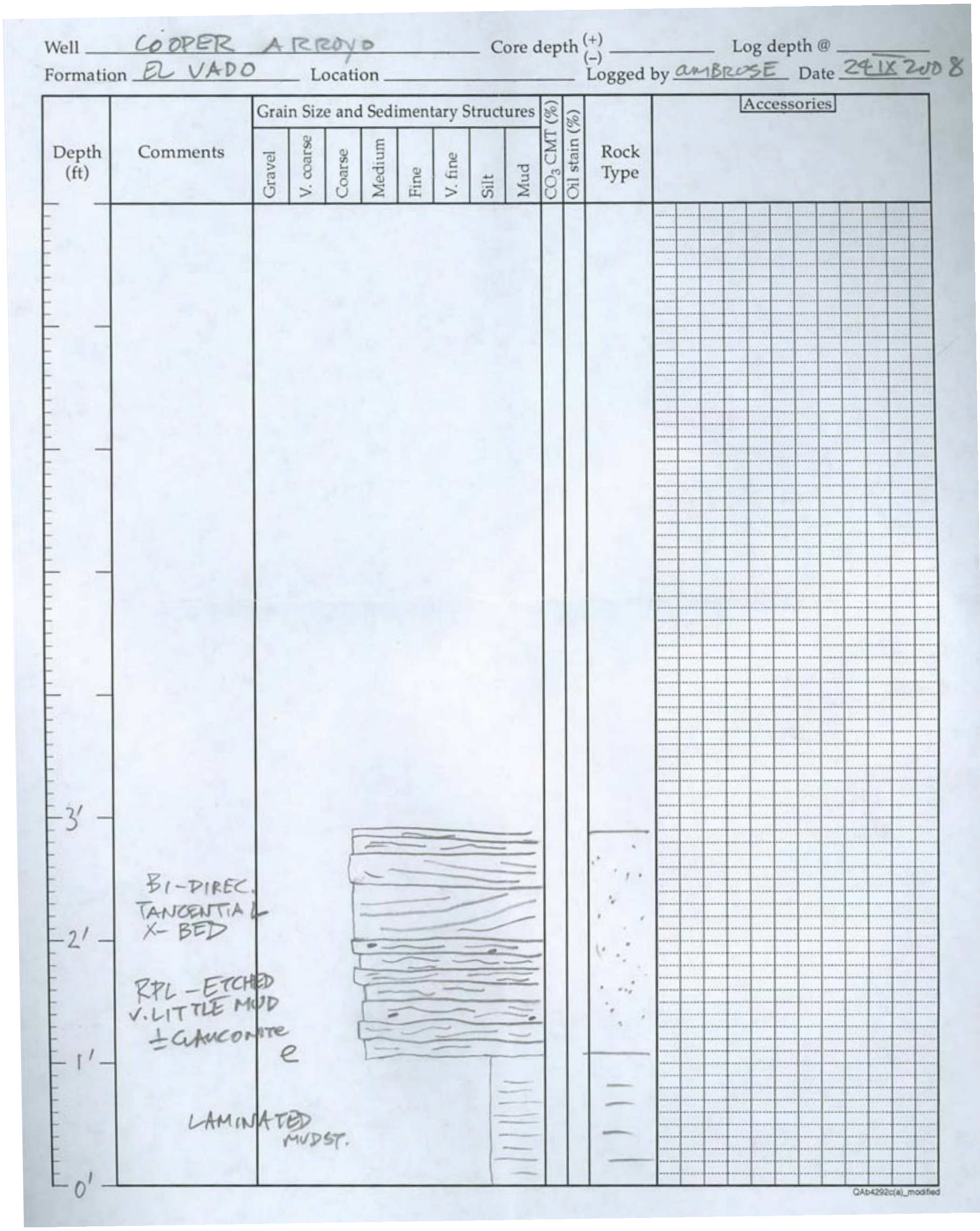


Figure A.3: Measured section of the Cooper Arroyo Sandstone by William Ambrose (Bureau of Economic Geology, University of Texas at Austin) in 2008.

Figure A.4: Southern El Vado Sandstone outcrop with GR curve overlain on the outcrop. Measurements collected from a scintillometer.

Point	API 1	API 2	API 3	AVG API
1	120.4	119.7	111	117.0333
2	106	11.6	104.1	73.9
3	93.2	90.7	95.7	93.2
4	95.1	91	92.3	92.8
5	85.4	88.2	86.7	86.76667
6	88.2	95.4	91.3	91.63333
7	96	94.8	94.2	95
8	80.4	78.9	82.6	80.63333
9	86.4	80.2	93.8	86.8
10	83.9	78.9	84.8	82.53333
11	80.4	72.9	77.9	77.06667
12	78.9	85.1	76.1	80.03333
13	77.6	87.9	84.5	83.33333
14	96.3	94.2	98.8	96.43333
15	89.8	92.3	89.5	90.53333
16	92	96	95.4	94.46667
17	88.2	87	86	87.06667
18	97.6	89.8	84.8	90.73333
19	88.2	88.8	83.9	86.96667
20	82.7	85.1	84.5	84.1
21	79.5	77.6	81.7	79.6
22	83.2	87.3	87.6	86.03333
23	93.8	94.5	89.2	92.5
24	92.6	86.7	83.2	87.5

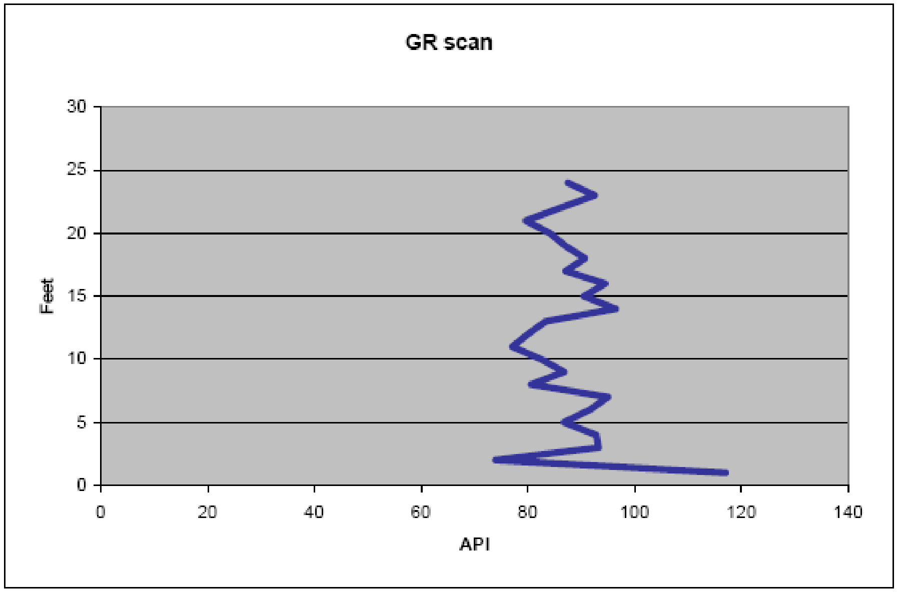


Figure: A.5: Values from the GR scan over a southern outcrop and the original curve.

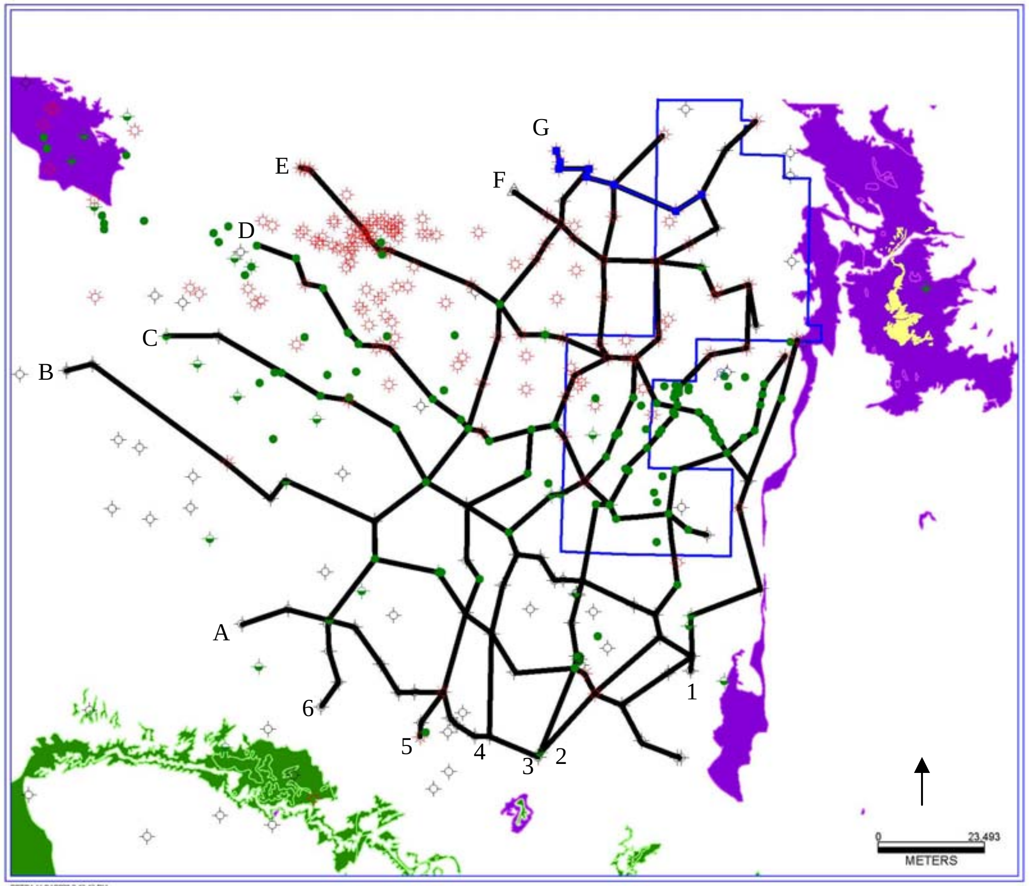


Figure: A.6: Map of the San Juan Basin, displaying cross-sections, Mancos Shale outcrops (purple), Crevasse Canyon outcrops (green), and El Vado Sandstone outcrops (yellow). The 13 cross-sections are labeled 1-6 and A-G.

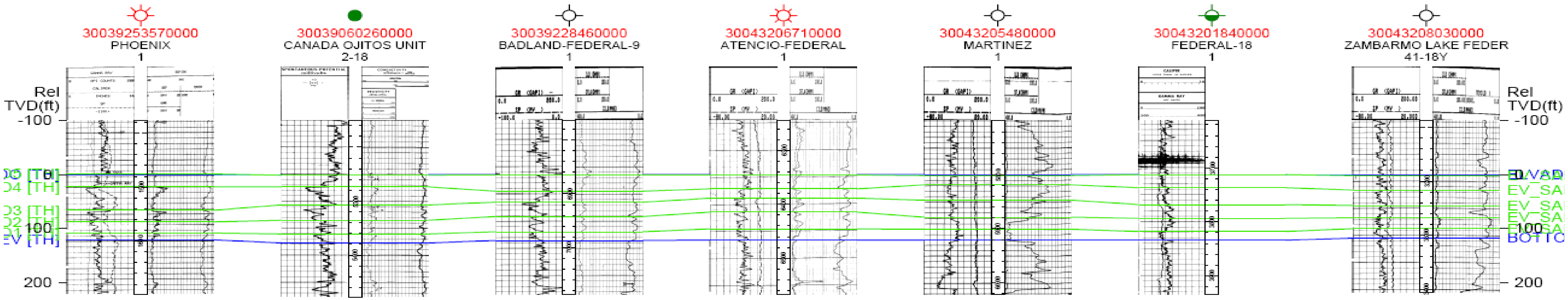


Figure A.7: Cross-section 1-1', oriented northeast – southwest. Well logs are datumed on the top of the El Vado Sandstone. Blue lines indicate top and bottom of the El Vado and green lines indicate individual cycles (starting with 1 through 5).

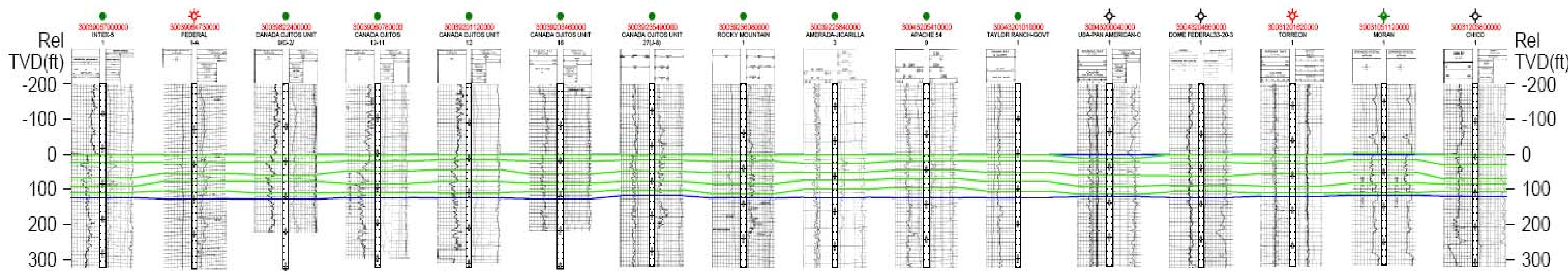


Figure A.8: Cross-section 2-2', oriented northeast – southwest. Well logs are datumed on the top of the El Vado Sandstone. Blue lines indicate top and bottom of the El Vado and green lines indicate individual cycles (starting with 1 through 5).

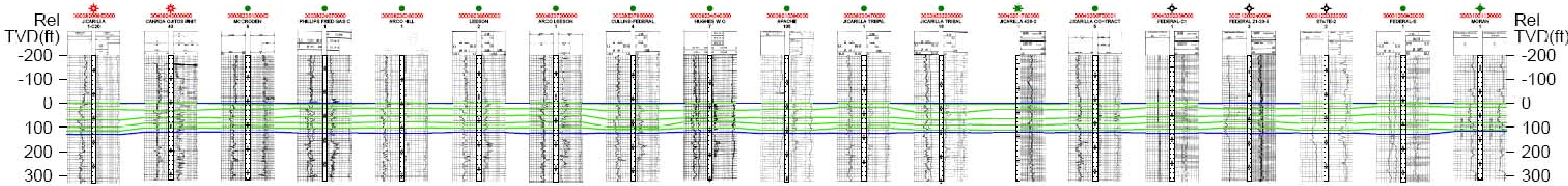


Figure A.9: Cross-section 3-3', oriented northeast – southwest. Well logs are datumed on the top of the El Vado Sandstone. Blue lines indicate top and bottom of the El Vado and green lines indicate individual cycles (starting with 1 through 5).

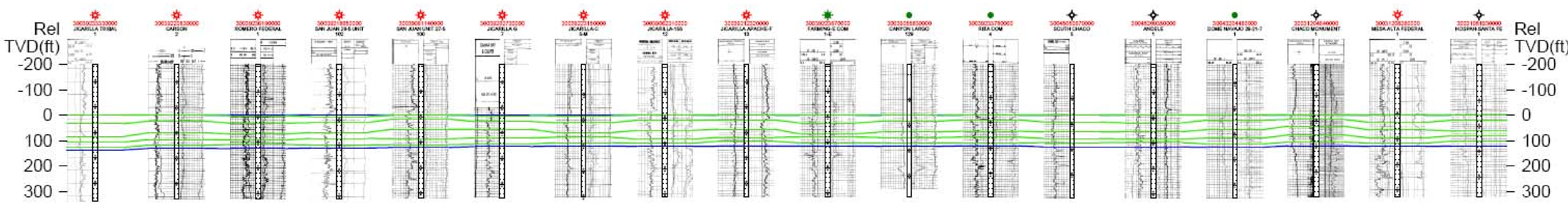


Figure A.10: Cross-section 5-5', oriented northeast – southwest. Well logs are datumed on the top of the El Vado Sandstone. Blue lines indicate top and bottom of the El Vado and green lines indicate individual cycles (starting with 1 through 5).

Figure A.11: Cross-section 6-6', oriented northeast – southwest. Well logs are datumed on the top of the El Vado Sandstone. Blue lines indicate top and bottom of the El Vado and green lines indicate individual cycles (starting with 1 through 5).

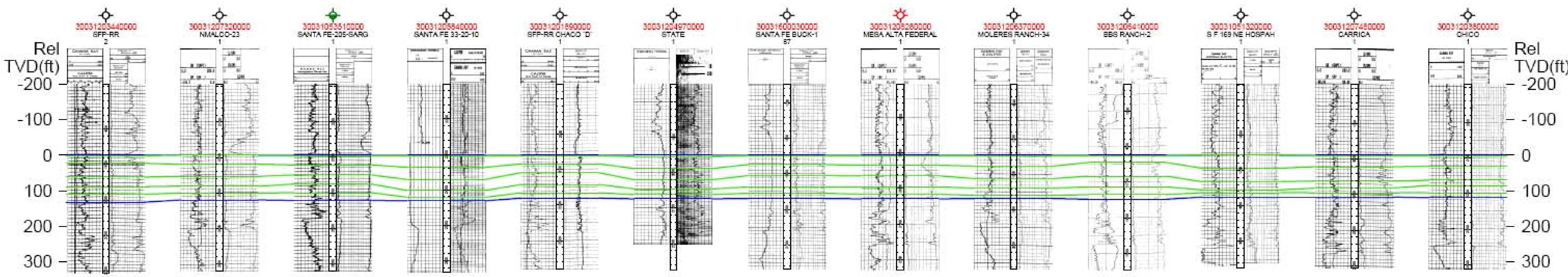


Figure A.12: Cross-section A-A', oriented northwest – southeast. Well logs are datumed on the top of the El Vado Sandstone. Blue lines indicate top and bottom of the El Vado and green lines indicate individual cycles (starting with 1 through 5).

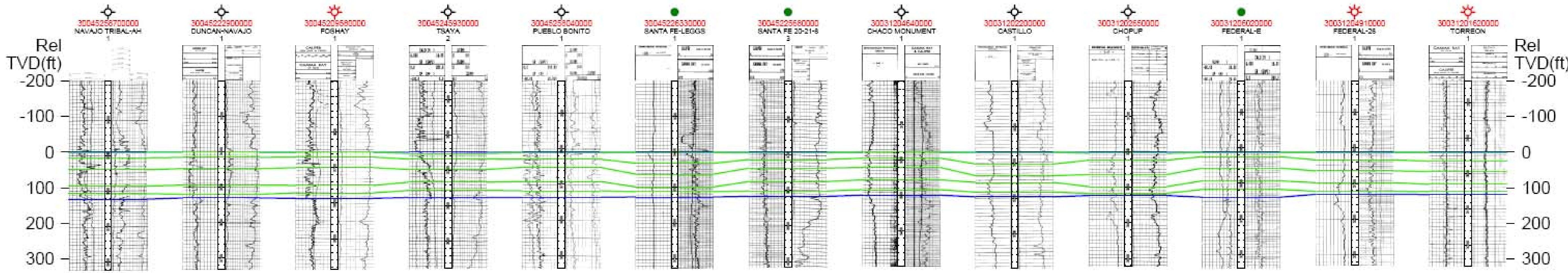


Figure A.13: Cross-section B-B', oriented northwest – southeast. Well logs are datumed on the top of the El Vado Sandstone. Blue lines indicate top and bottom of the El Vado and green lines indicate individual cycles (starting with 1 through 5).

Figure A.14: Cross-section C-C', oriented northwest – southeast. Well logs are datumed on the top of the El Vado Sandstone. Blue lines indicate top and bottom of the El Vado and green lines indicate individual cycles (starting with 1 through 5).

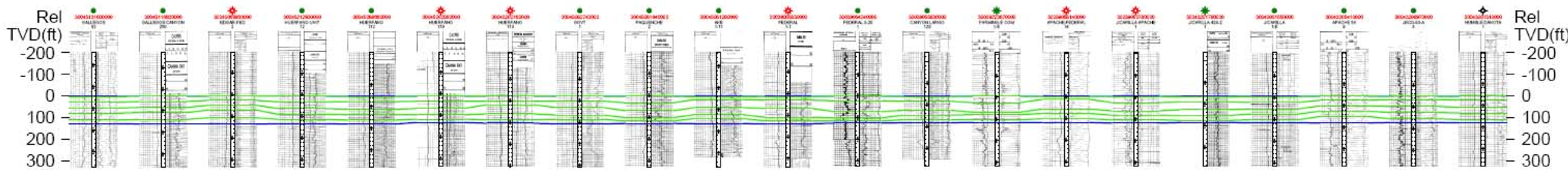


Figure A.15: Cross-section D-D', oriented northwest – southeast. Well logs are datumed on the top of the El Vado Sandstone. Blue lines indicate top and bottom of the El Vado and green lines indicate individual cycles (starting with 1 through 5).

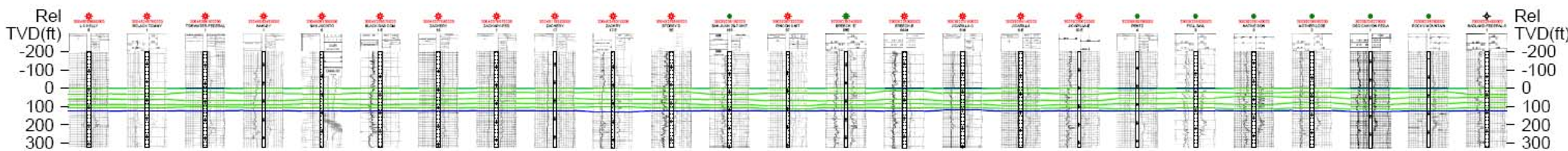


Figure A.16: Cross-section E-E', oriented northwest – southeast. Well logs are datumed on the top of the El Vado Sandstone. Blue lines indicate top and bottom of the El Vado and green lines indicate individual cycles (starting with 1 through 5).

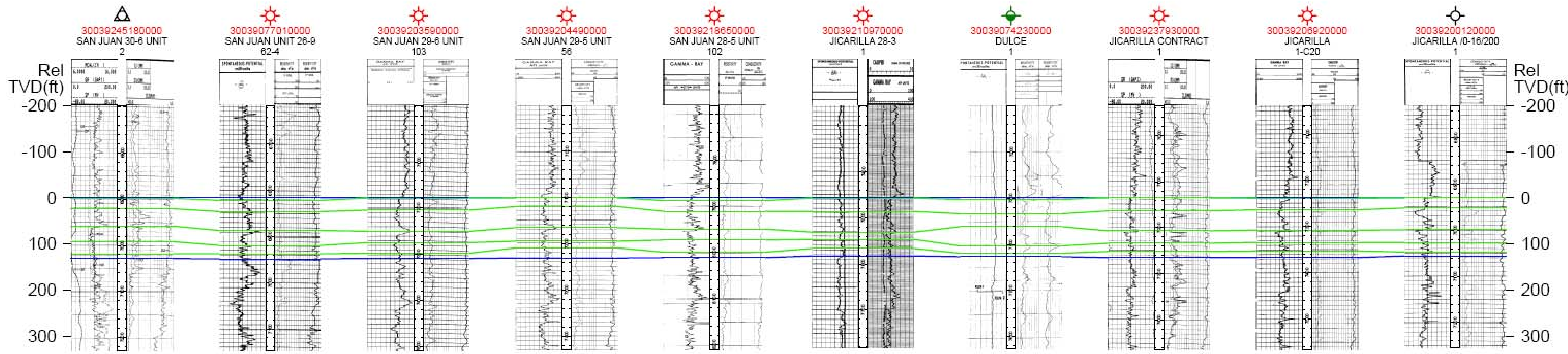


Figure A.17: Cross-section F-F', oriented northwest – southeast. Well logs are datumed on the top of the El Vado Sandstone. Blue lines indicate top and bottom of the El Vado and green lines indicate individual cycles (starting with 1 through 5).

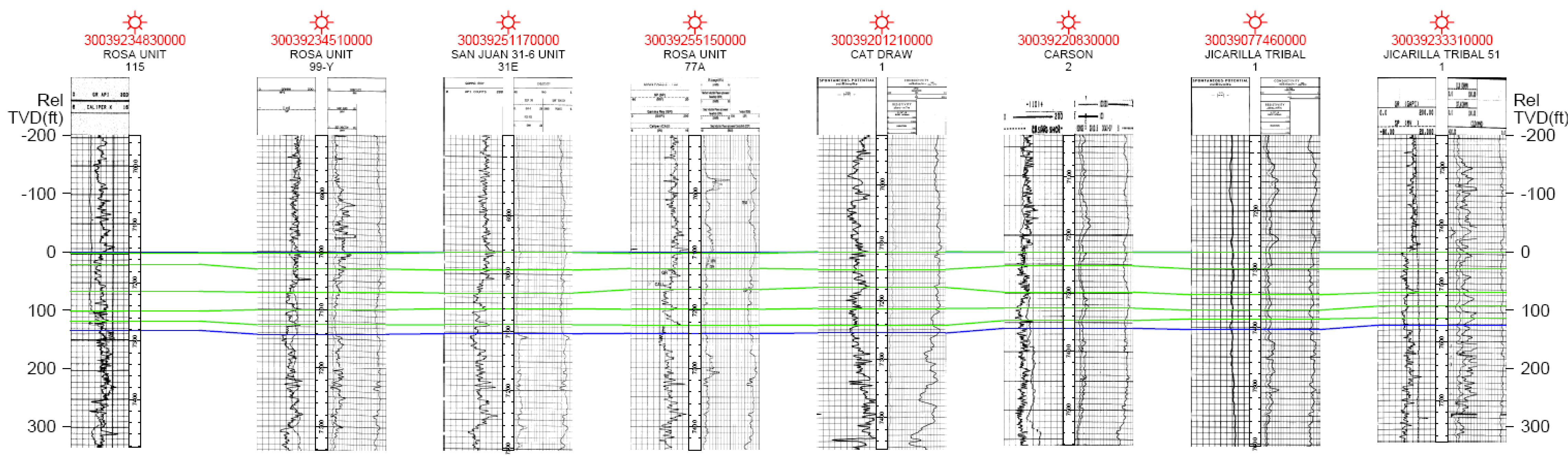


Figure A.18: Cross-section G-G', oriented northwest – southeast. Well logs are datumed on the top of the El Vado Sandstone. Blue lines indicate top and bottom of the El Vado and green lines indicate individual cycles (starting with 1 through 5).

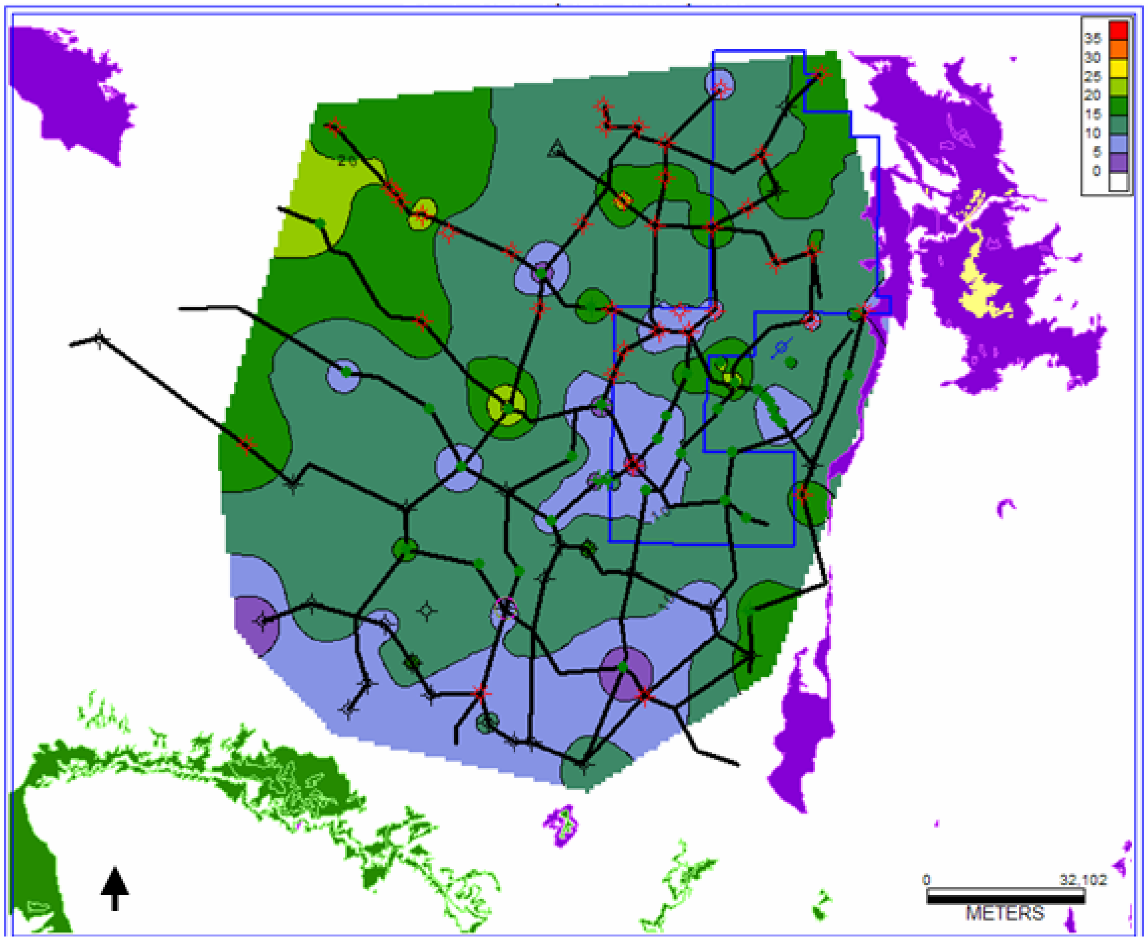


Figure A.19: Net sand map of Cycle 1, using 105 API sand-shale cutoff.

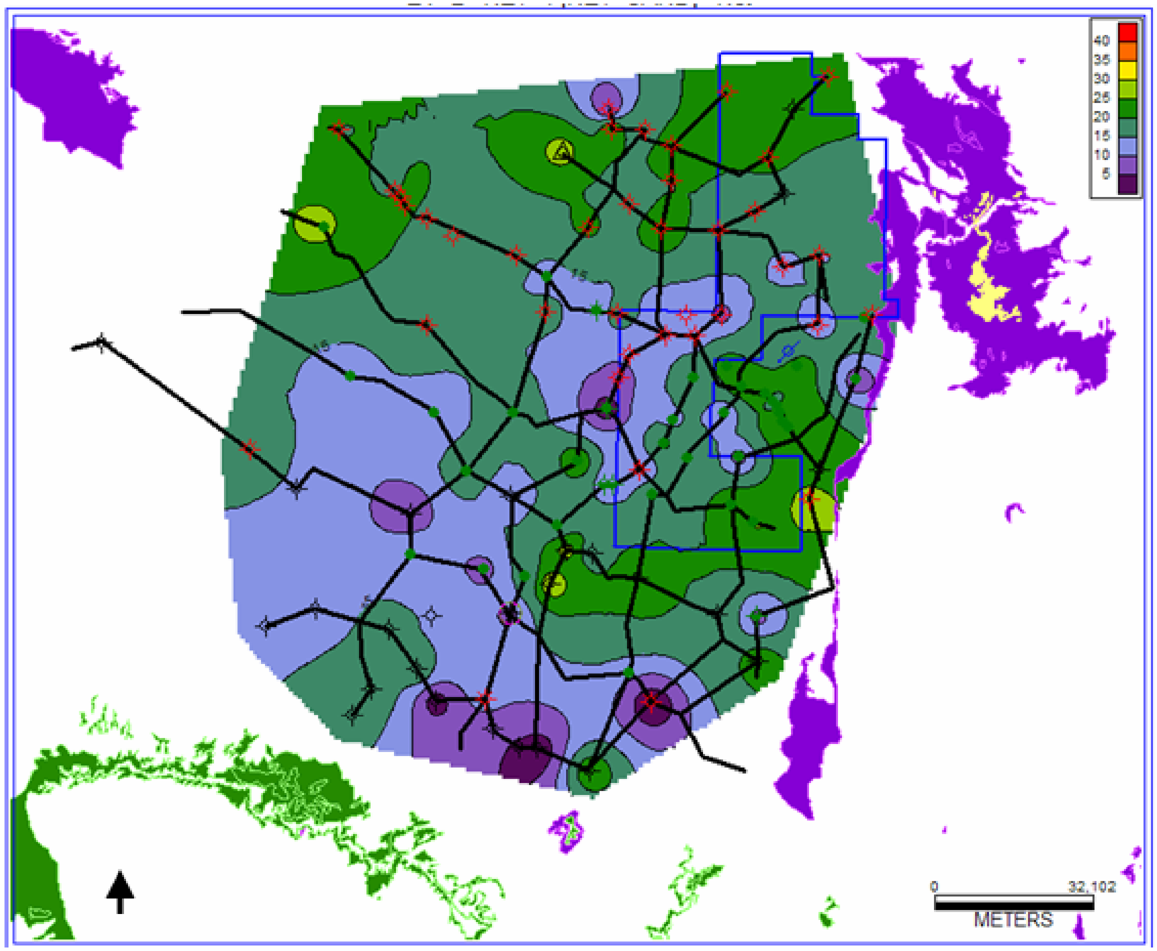


Figure A.20: Net sand map of Cycle 2, using 105 API sand-shale cutoff.

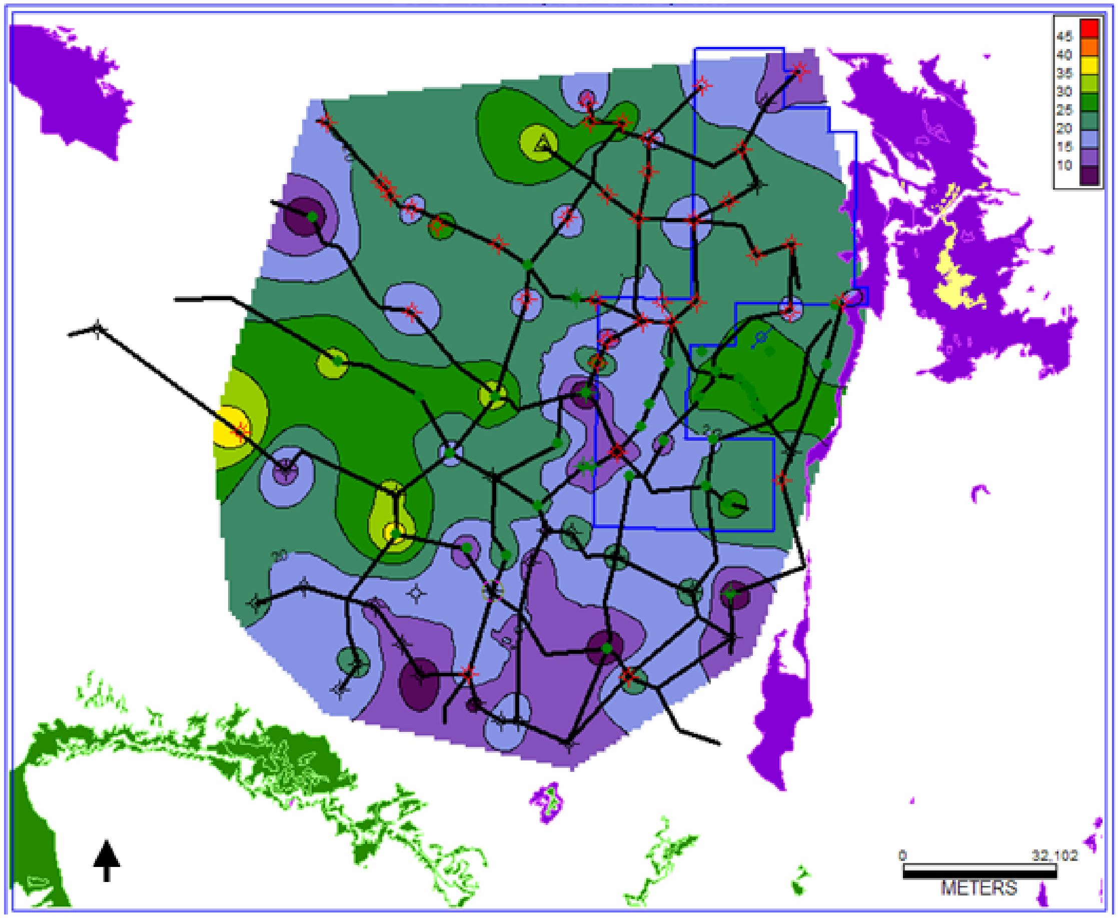


Figure A.21: Net sand map of Cycle 3, using 105 API sand-shale cutoff.

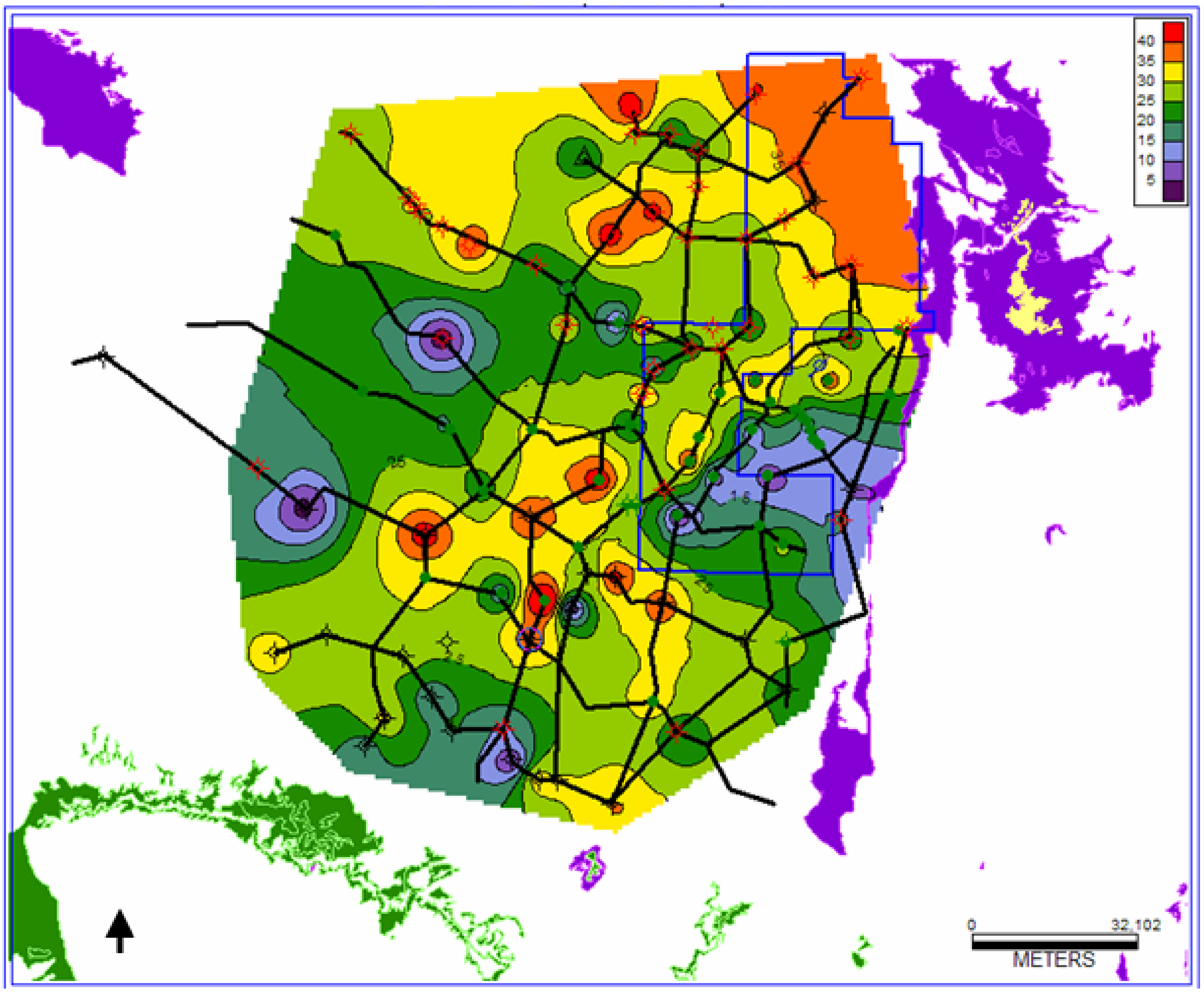


Figure A.22: Net sand map of Cycle 4, using 105 API sand-shale cutoff.

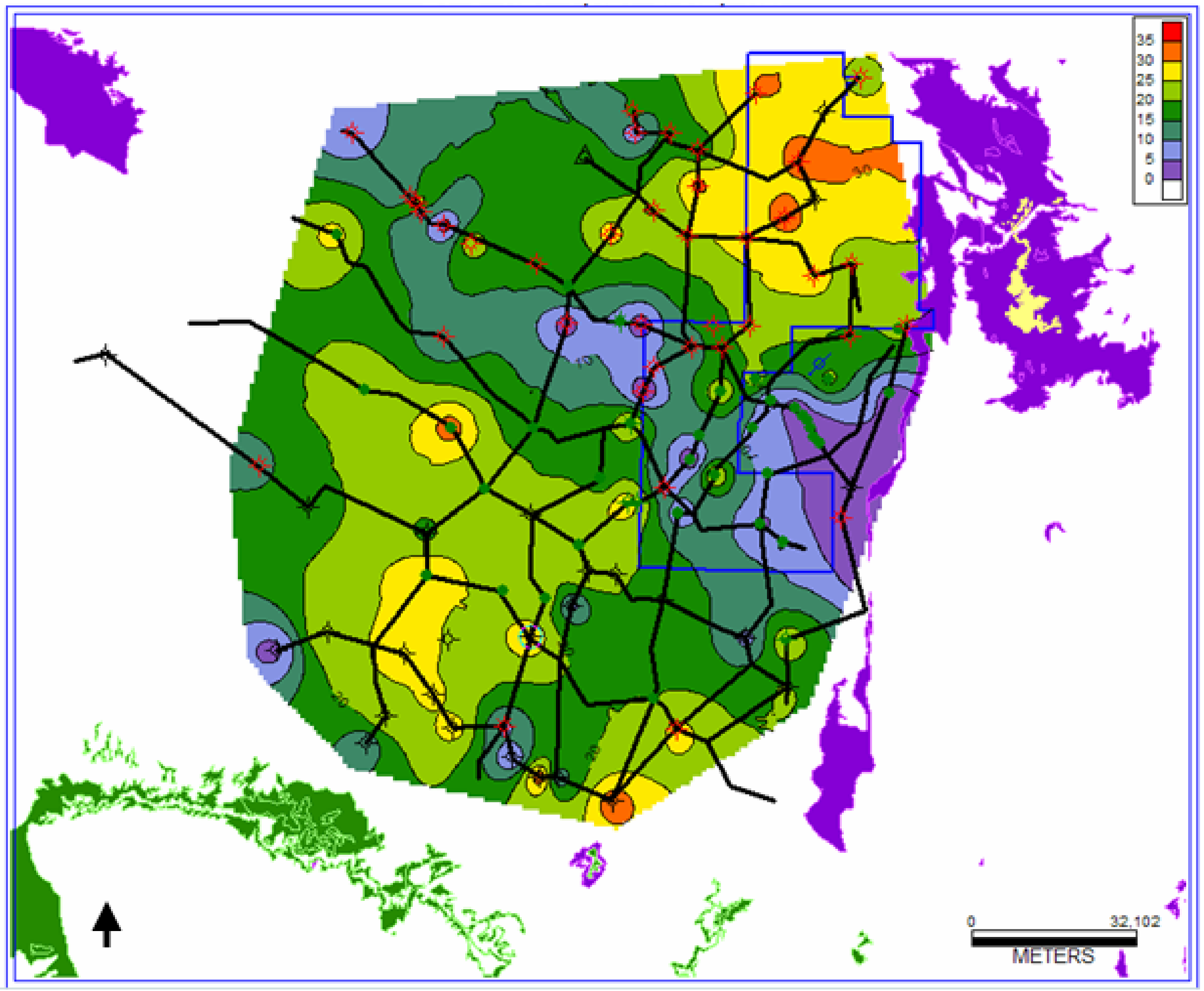


Figure A.23: Net sand map of Cycle 5, using 105 API sand-shale cutoff.

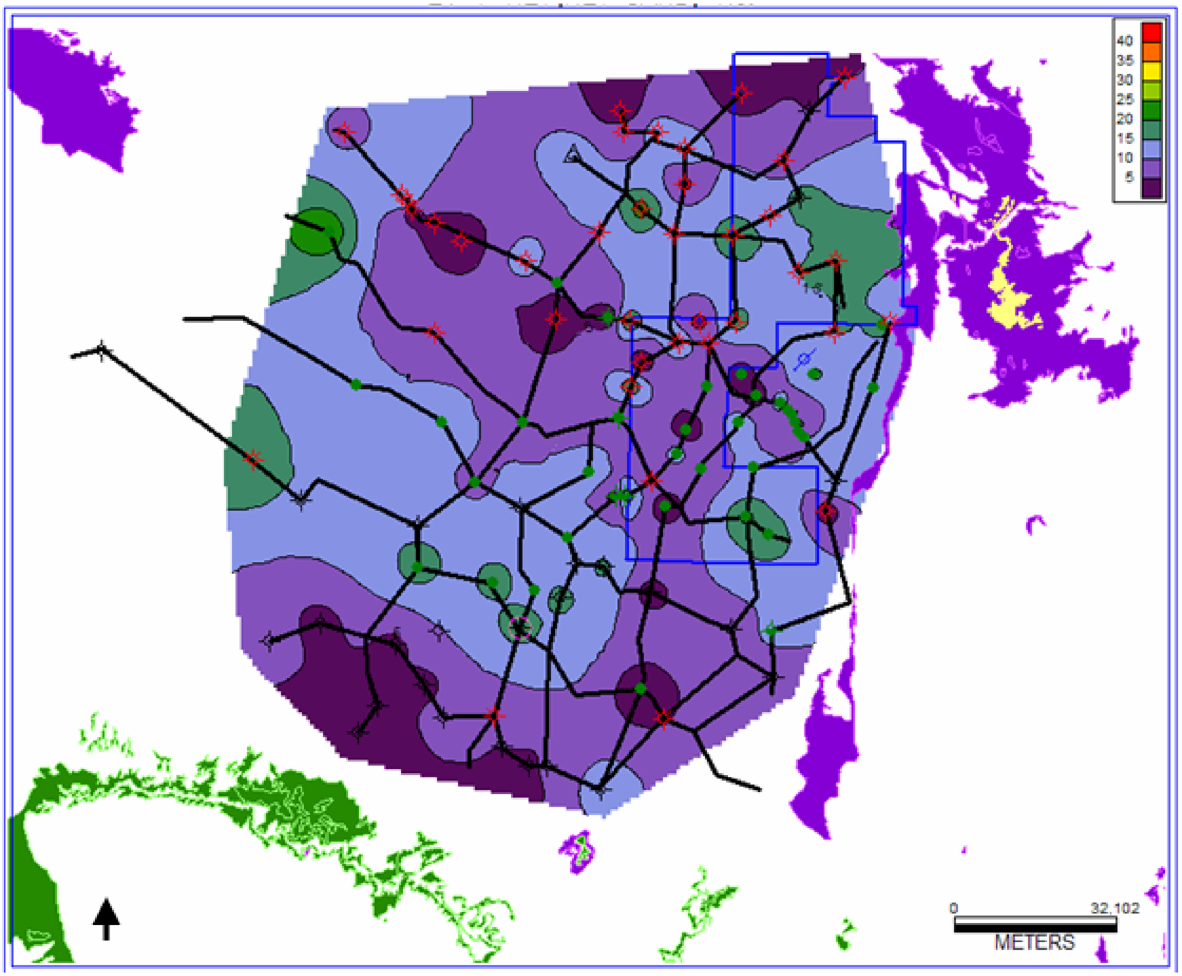


Figure A.24: Net sand map of Cycle 1, using 80 API sand-shale cutoff.

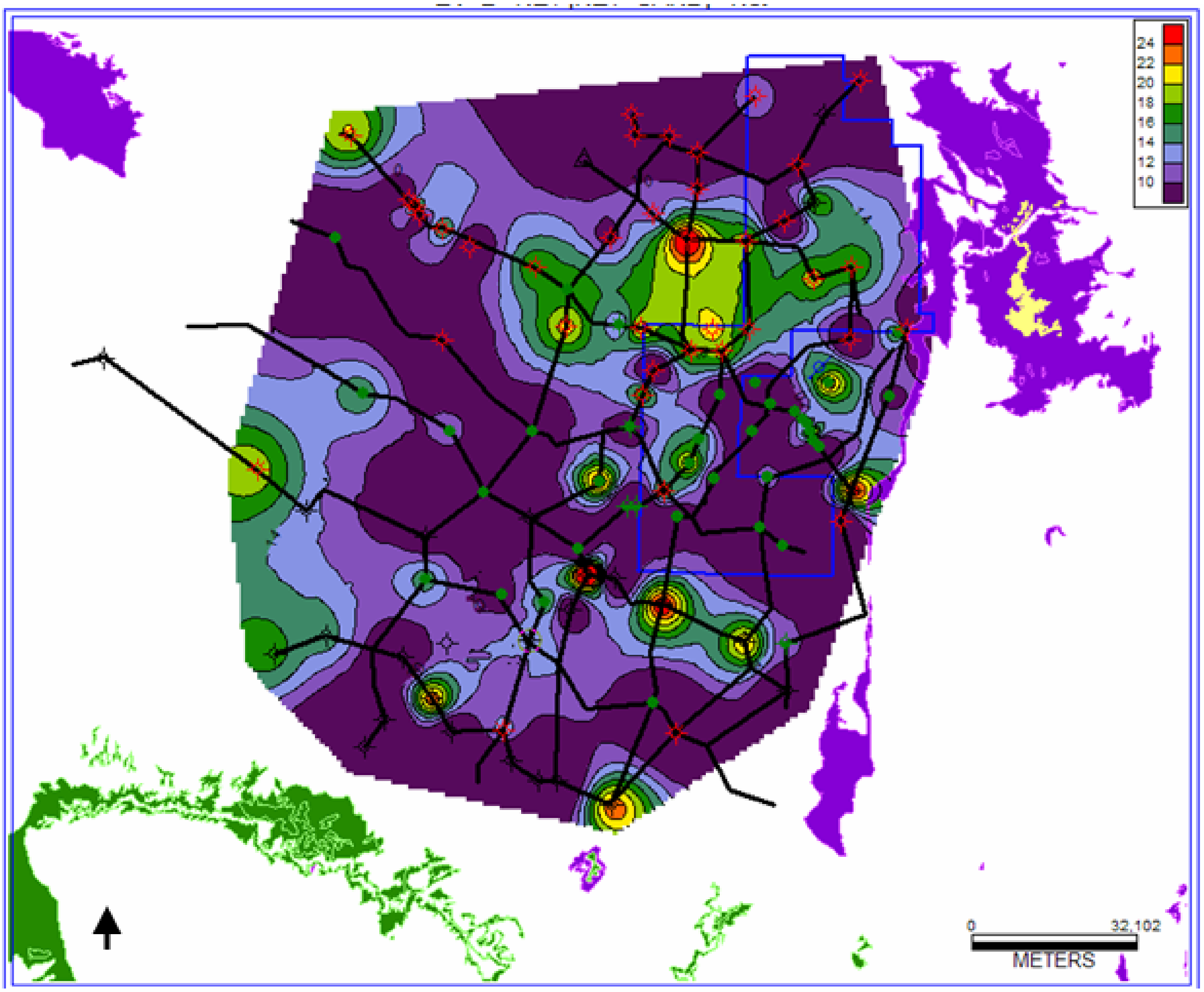


Figure A.25: Net sand map of Cycle 2, using 80 API sand-shale cutoff.

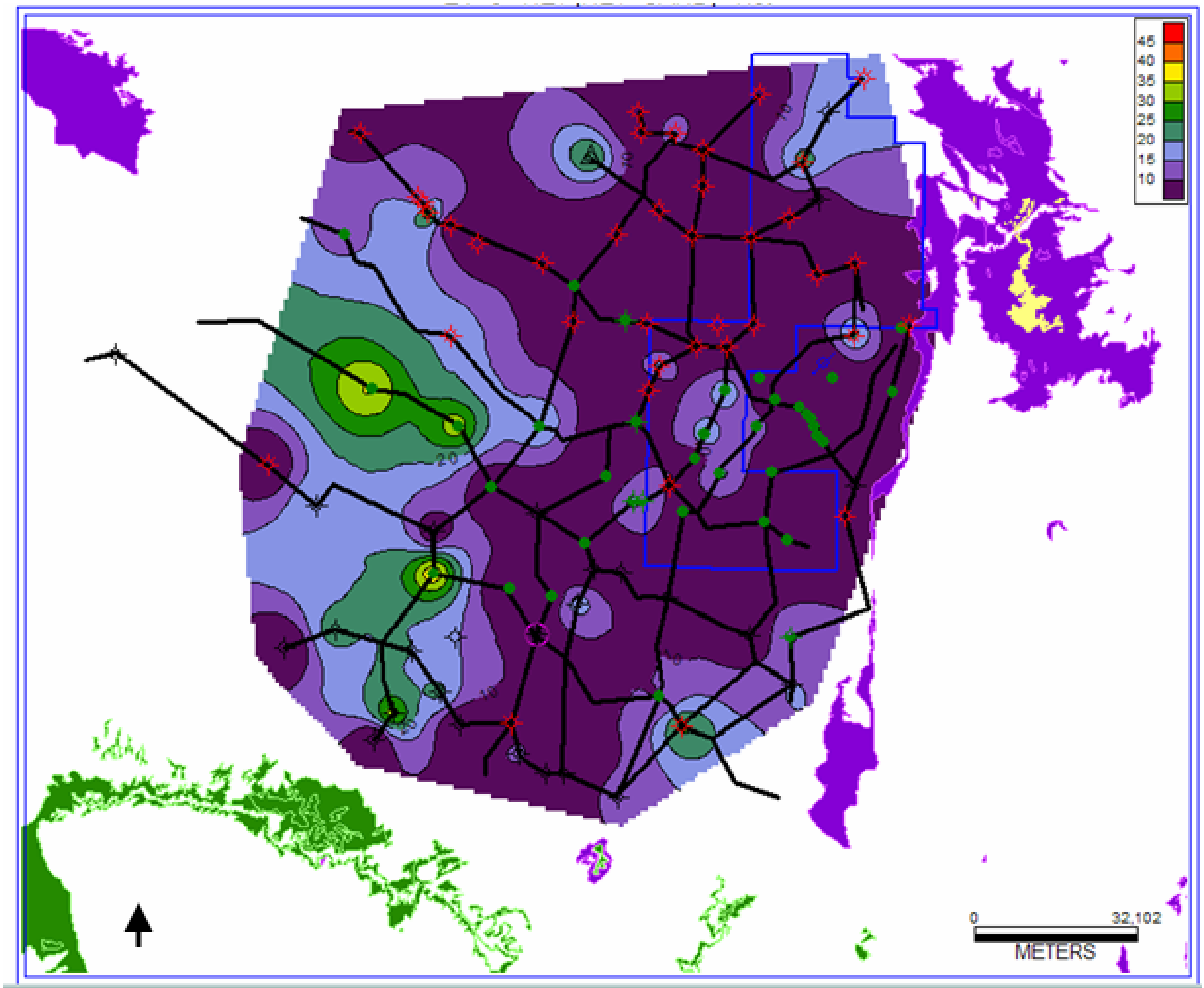


Figure A.26: Net sand map of Cycle 3, using 80 API sand-shale cutoff.

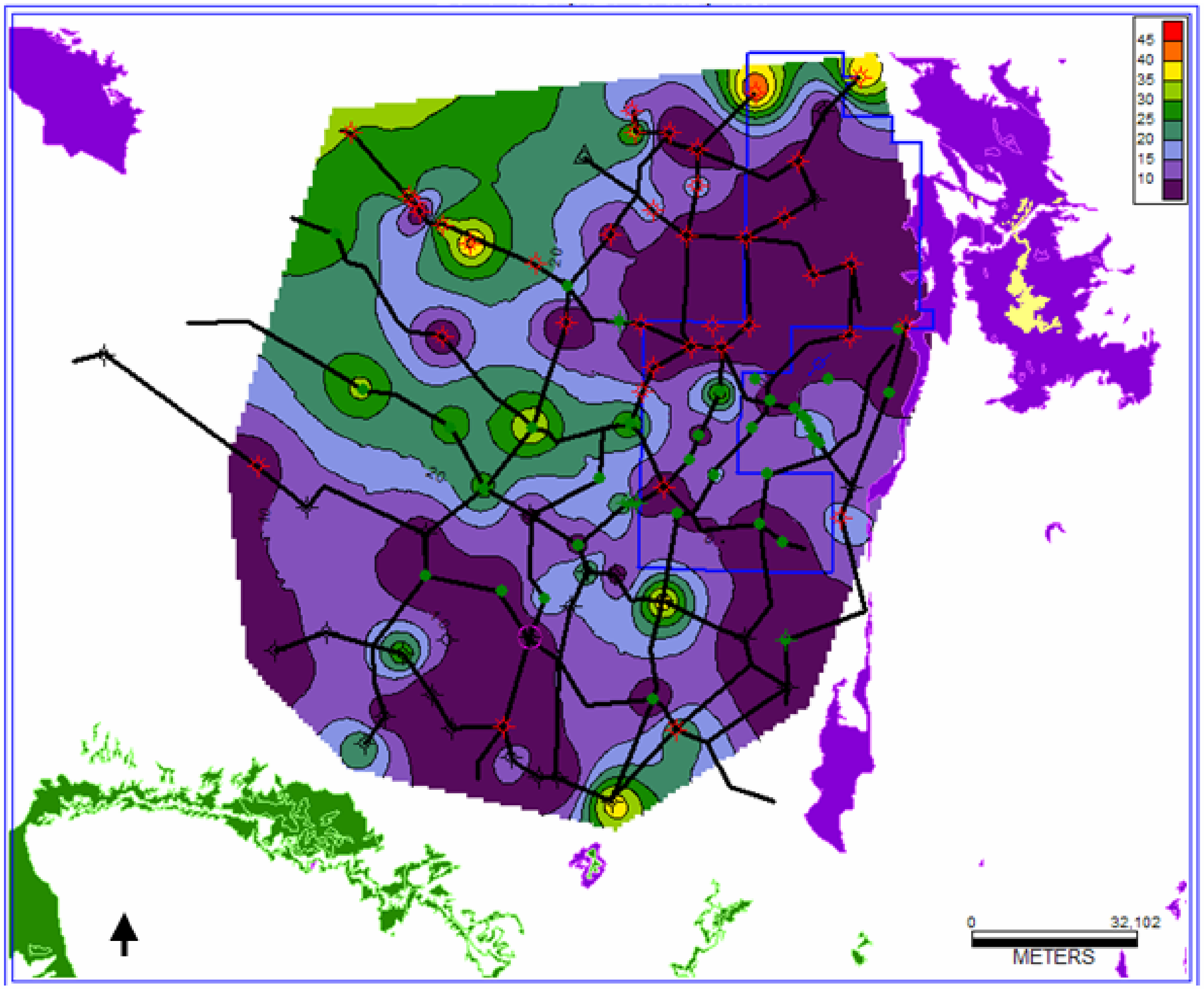


Figure A.27: Net sand map of Cycle 4, using 80 API sand-shale cutoff.

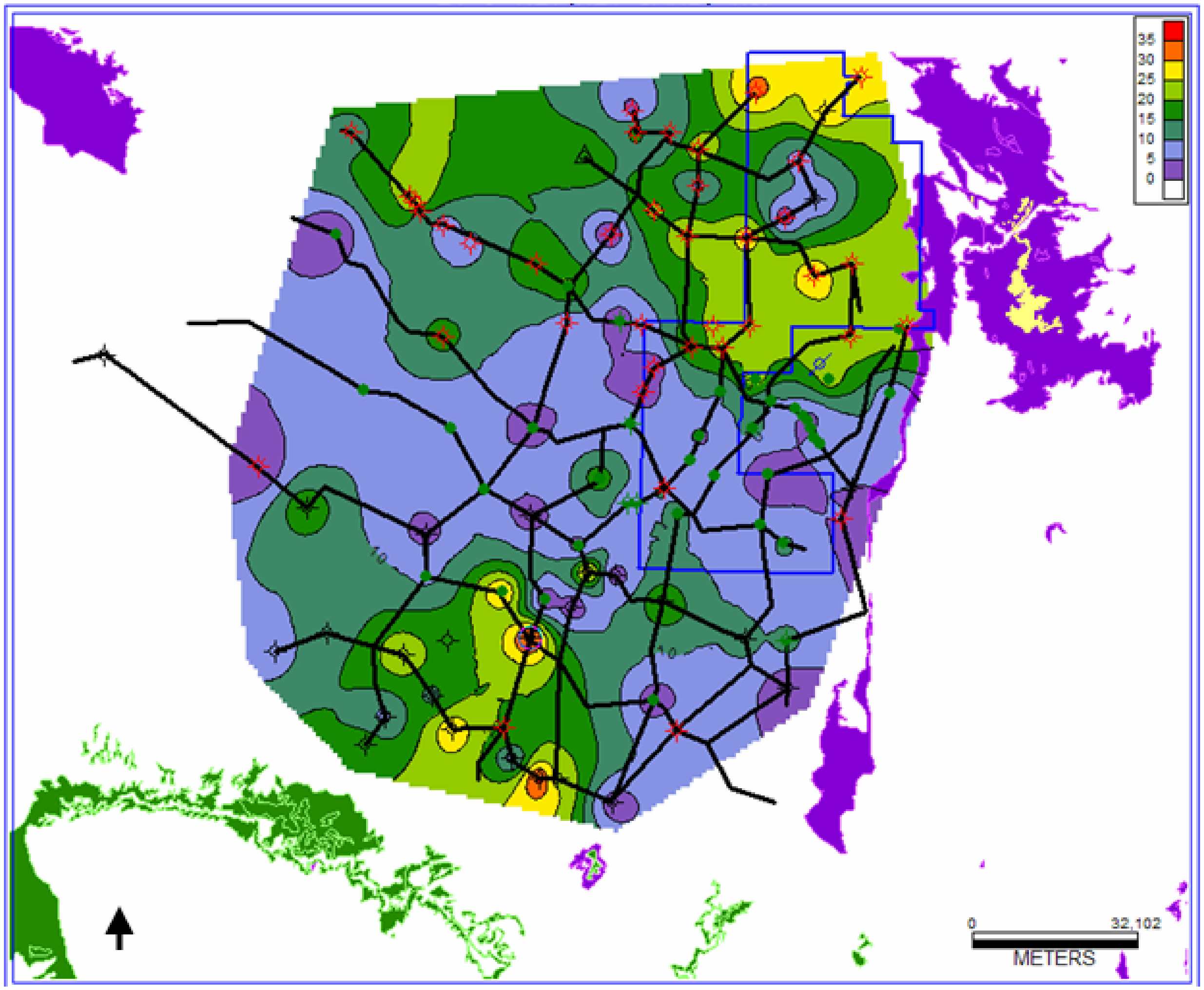


Figure A.28: Net sand map of Cycle 5, using 80 API sand-shale cutoff.

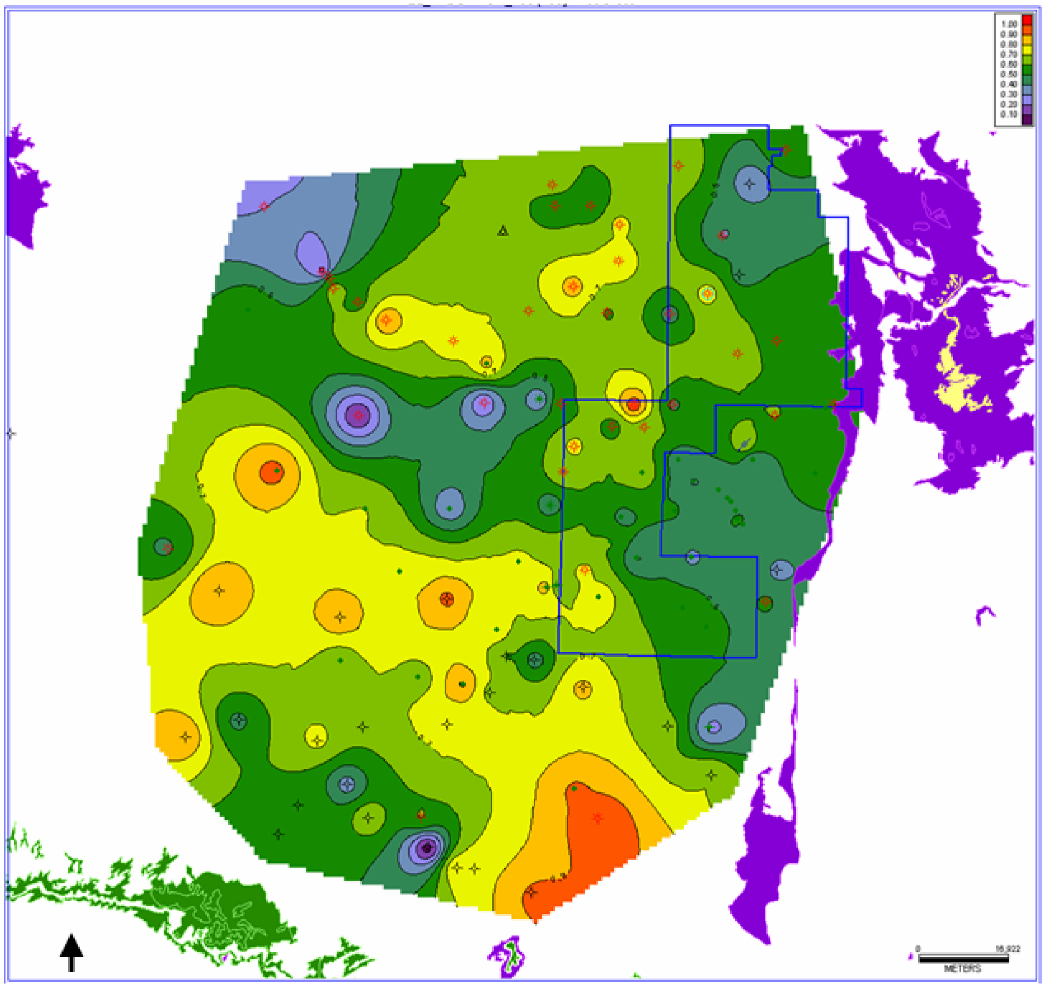


Figure A.29: Net to gross sand map of entire El Vado interval, using 100 API sand-shale cutoff. Color scale from 0.10 to 1.00 (N/G ratio) with 0.05 increments, with red beginning the highest value.

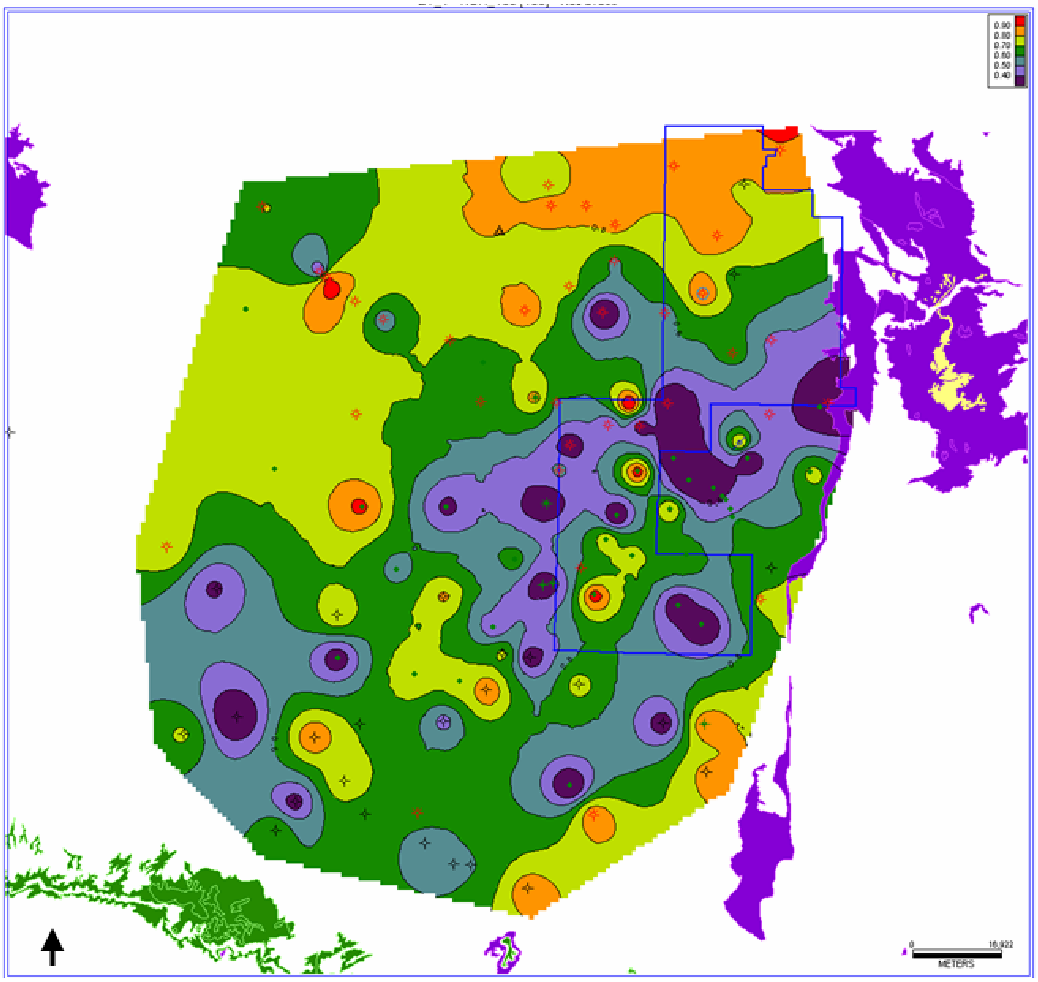


Figure A.30: Net to gross sand map of Cycle 1, using 100 API sand-shale cutoff. Color scale from 0.40 to 0.80 (N/G ratio) with 0.10 increments, with red beginning the highest value.

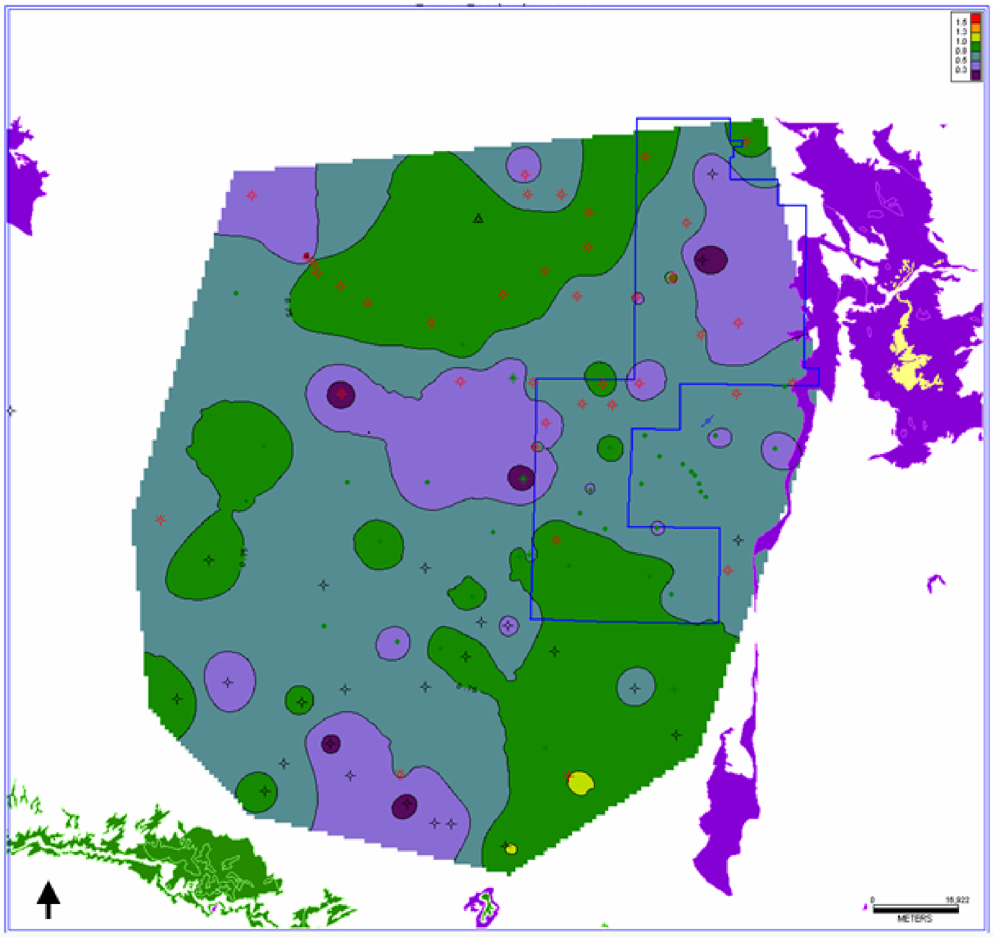


Figure A.31: Net to gross sand map of Cycle 2, using 100 API sand-shale cutoff. Color scale from 0.2 to 1.5 (N/G ratio) with 0.30 increments, with red beginning the highest value.

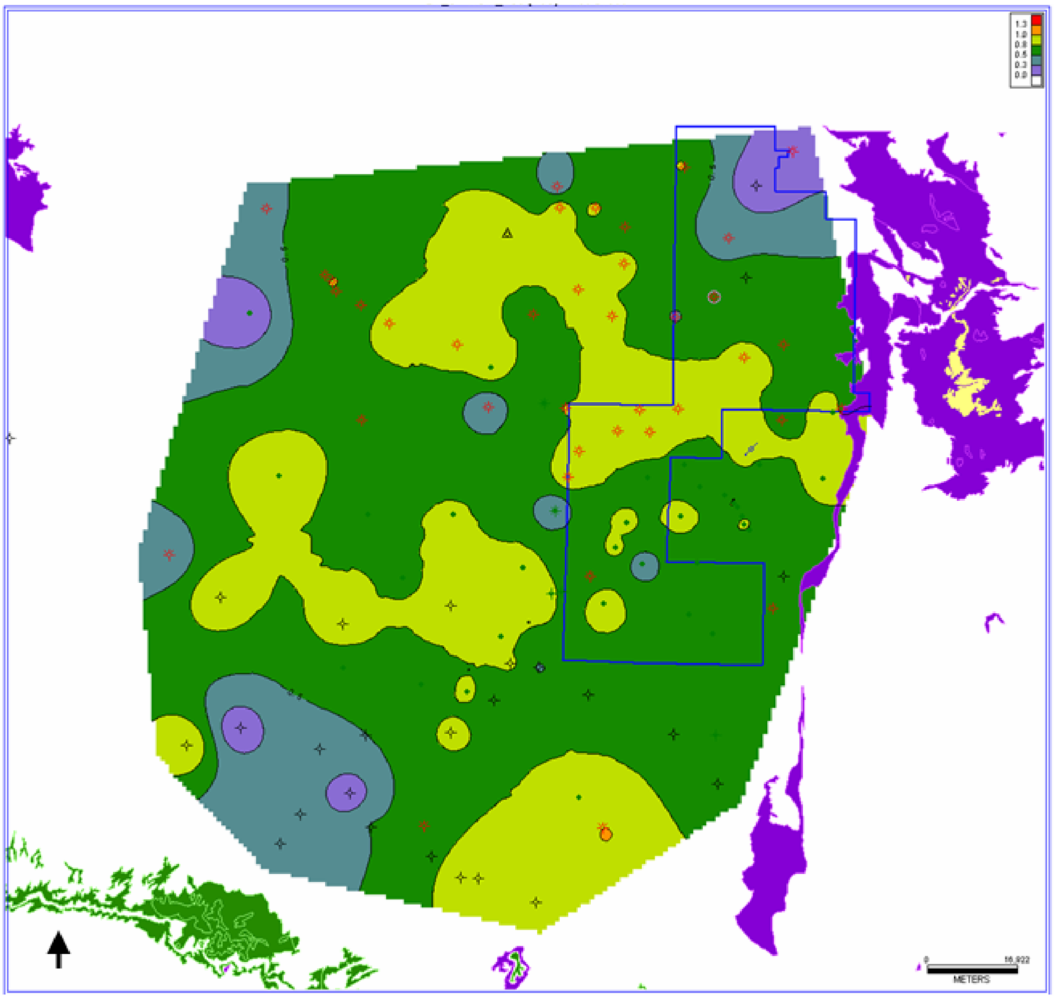


Figure A.32: Net to gross sand map of Cycle 3, using 100 API sand-shale cutoff. Color scale from 0.0 to 1.3 (N/G ratio) with 0.30 increments, with red beginning the highest value.

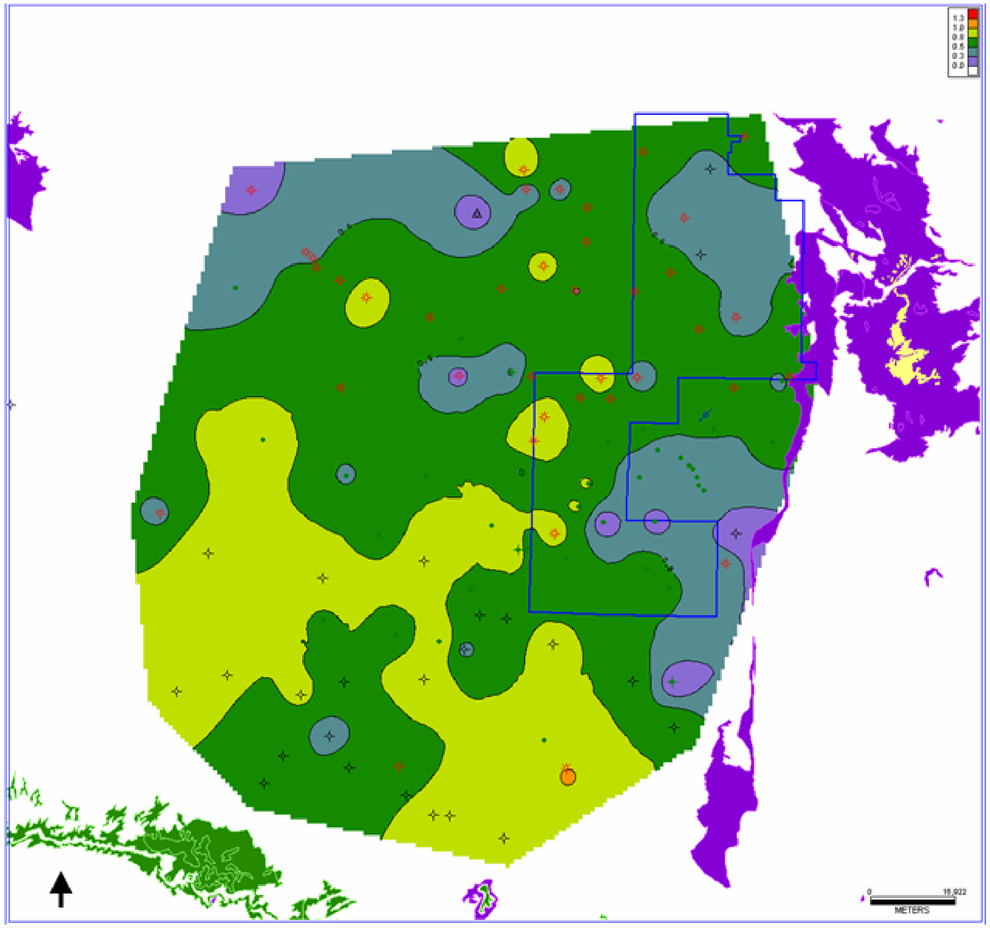


Figure A.33: Net to gross sand map of Cycle 4, using 100 API sand-shale cutoff. Color scale from 0.0 to 1.3 (N/G ratio) with 0.30 increments, with red beginning the highest value.

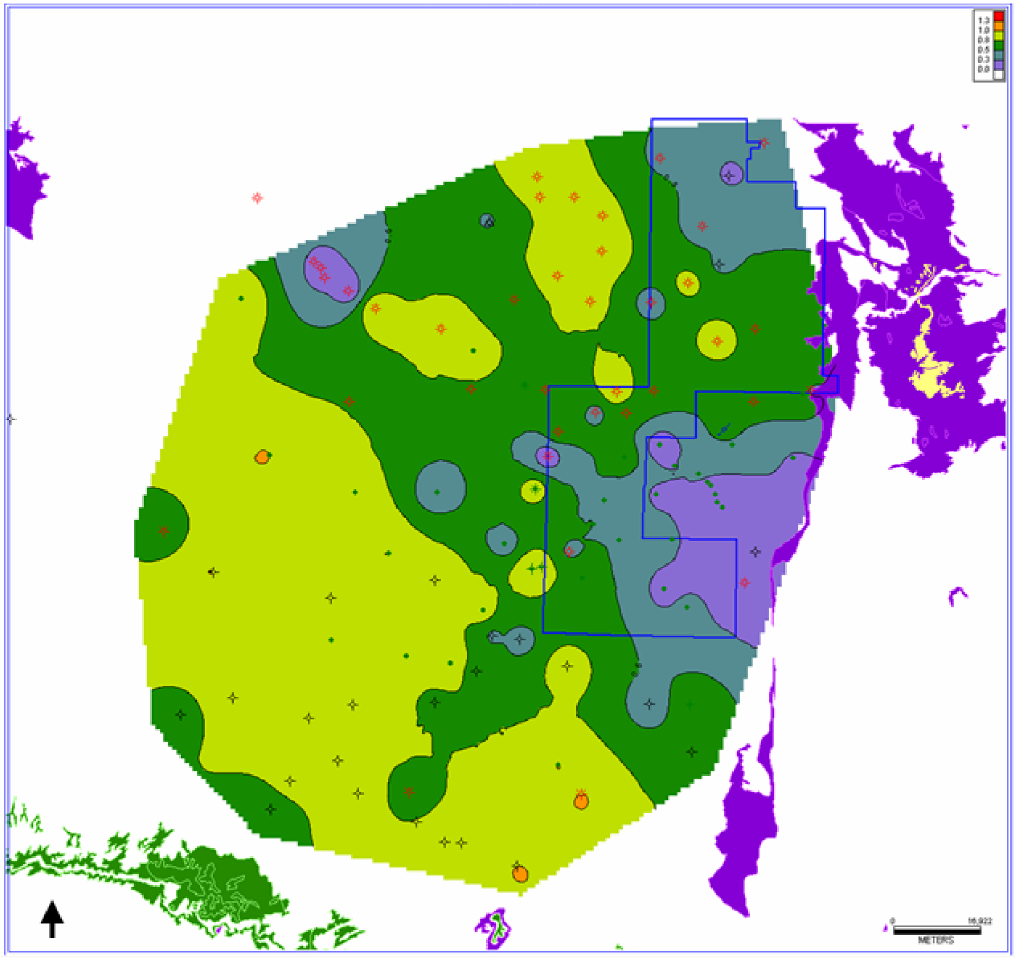


Figure A.34: Net to gross sand map of Cycle 5, using 100 API sand-shale cutoff. Color scale from 0.0 to 1.3 (N/G ratio) with 0.30 increments, with red beginning the highest value.

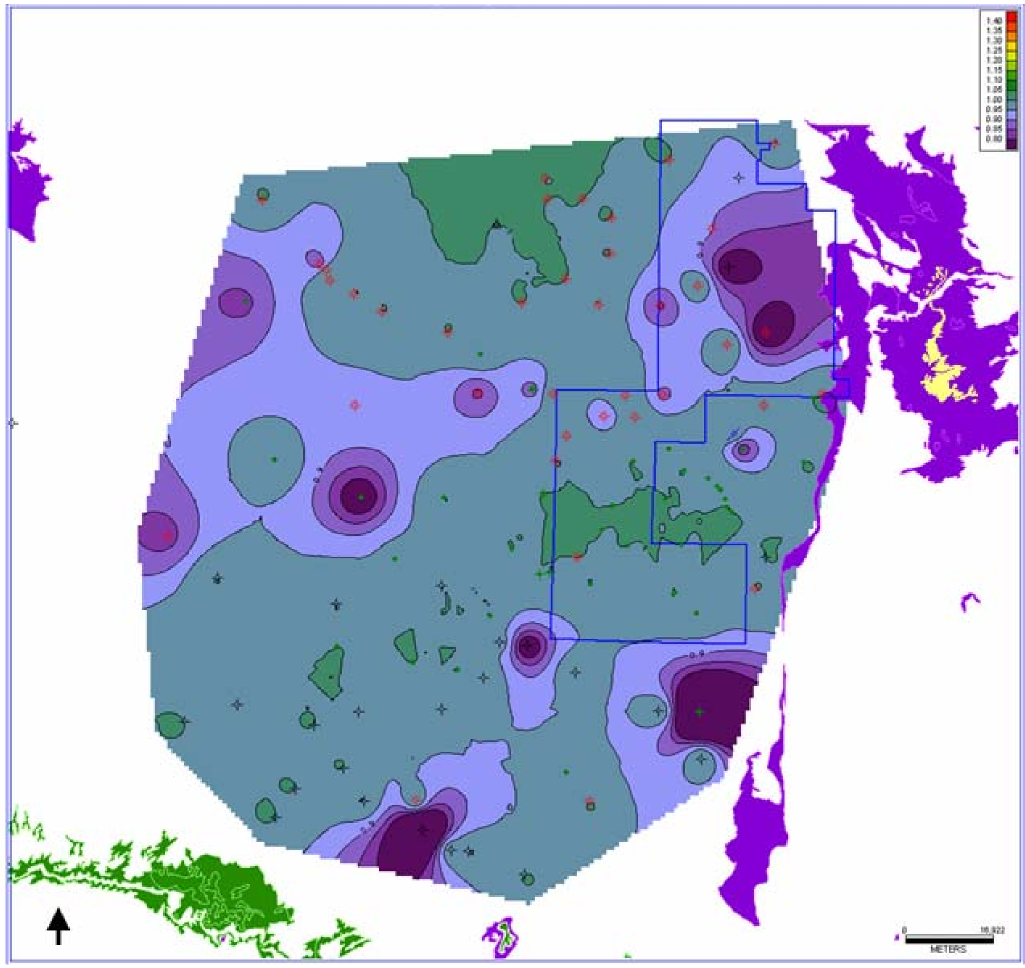


Figure A.35: Net to gross sand map of Cycle 2, using 120 API sand-shale cutoff. Color scale from 0.80 to 1.40 (N/G ratio) with 0.05 increments, with red beginning the highest value.

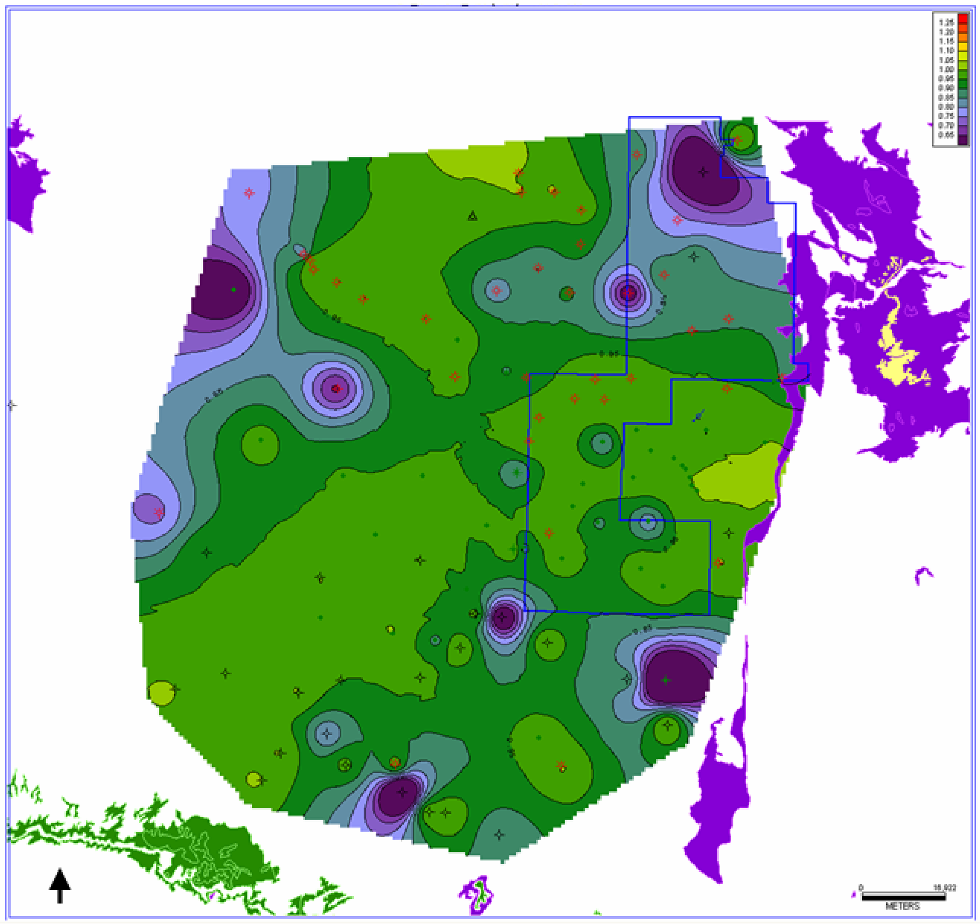


Figure A.36: Net to gross sand map of Cycle 3, using 120 API sand-shale cutoff. Color scale from 0.65 to 1.25 (N/G ratio) with 0.05 increments, with red beginning the highest value.

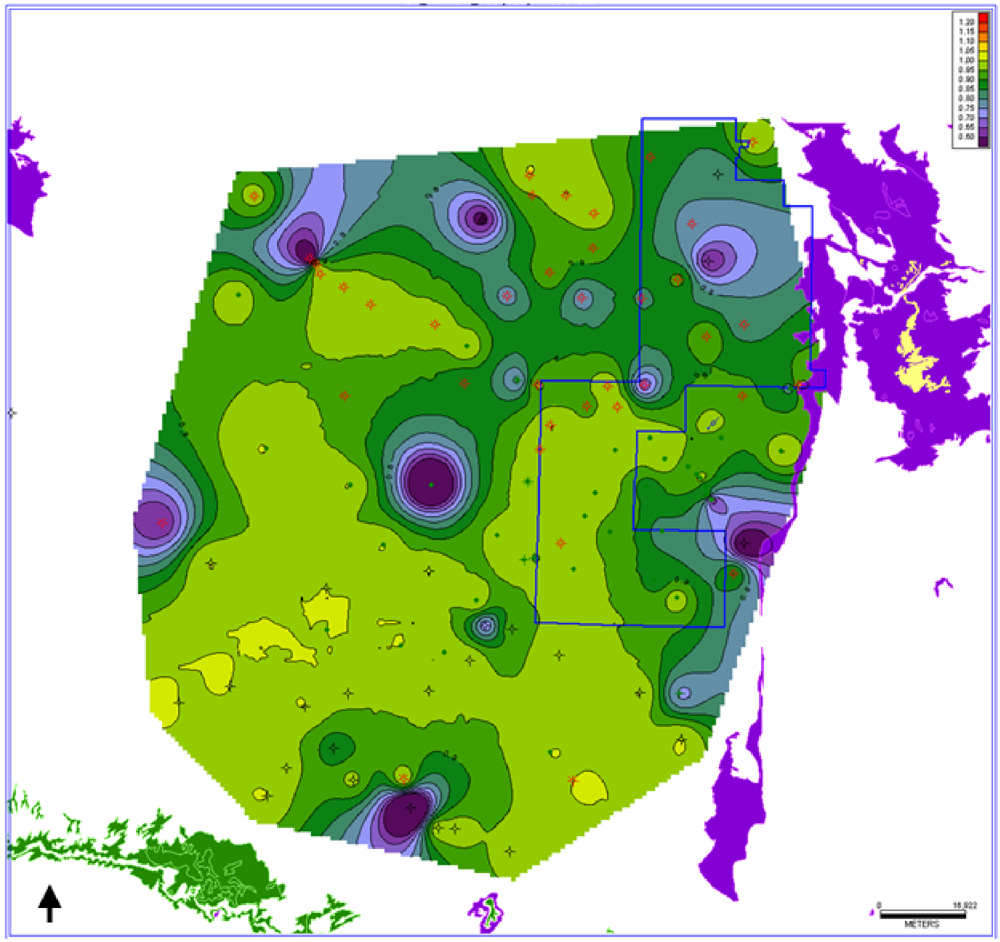


Figure A.37: Net to gross sand map of Cycle 4, using 120 API sand-shale cutoff. Color scale from 0.60 to 1.20 (N/G ratio) with 0.05 increments, with red beginning the highest value.

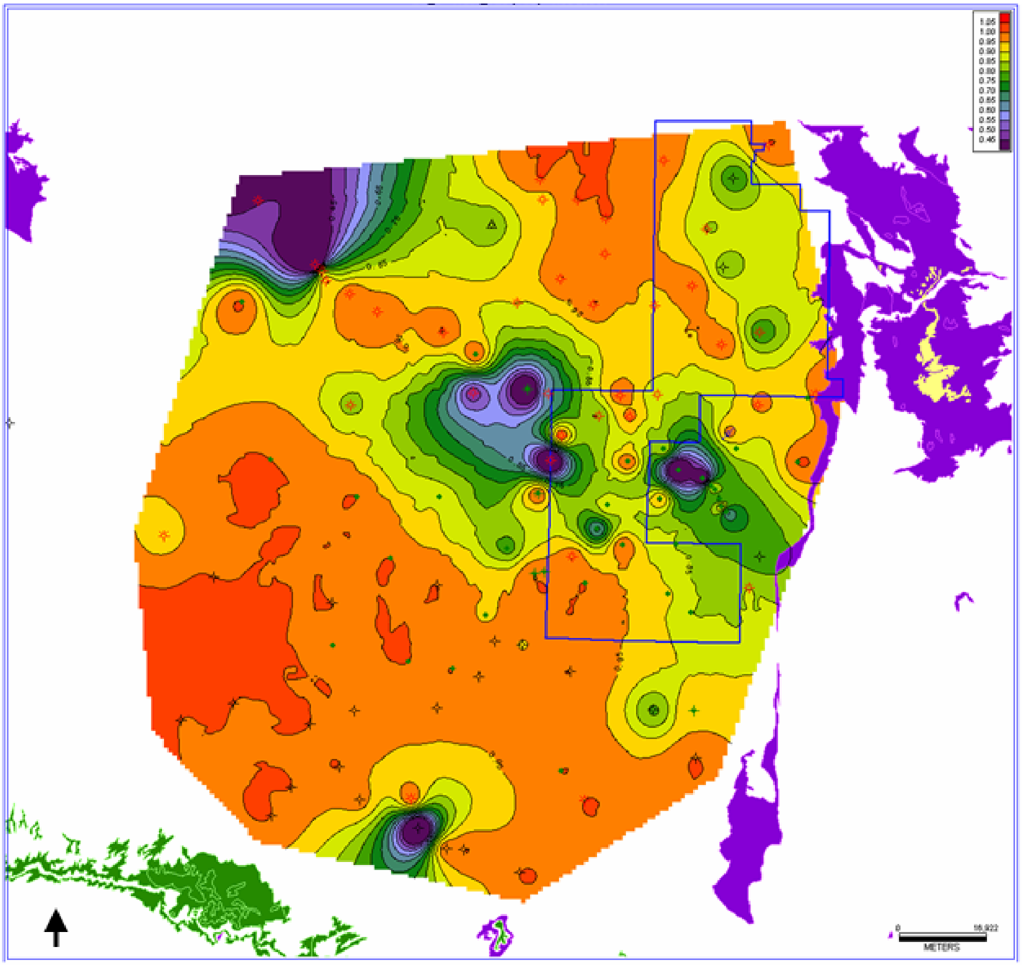


Figure A.38: Net to gross sand map of Cycle 5, using 120 API sand-shale cutoff. Color scale from 0.45 to 1.05 (N/G ratio) with 0.05 increments, with red beginning the highest value.

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